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TRANSACTIONS
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RELATIVE GEOIDAL UNDULATIONS FROM DEFLECTIONS OF THE VERTICAL

Carl I. Aslakson

Abstract--Shoran trilateration in the Bahama Islands permits the determination of the deflection of the vertical with considerable accuracy. The deflections observed to date show a striking correlation with the ocean-bottom gradients and with the available free-air anomaly gradients. This suggests the computation of relative geoidal heights by using strategically placed deflection observations. This paper describes a promising method of computing the relative undulations.

Introduction--At the present time there is in progress the most extensive electronic survey ever undertaken. The primary purpose of the survey is to provide accurate relative distances and azimuths between the numerous guided-missile tracking stations of the Air Force Missile Test Center Proving Ground. The extent of the project is shown in Figure 1. The survey is being executed by personnel of the United States Air Force and is being directed by the author as geodetic officer of the Air Force Missile Test Center.

From a geophysical standpoint, the area covered by this survey is one of the world's most interesting regions. A considerable amount of gravity-intensity data, both on land and at sea, has been gathered throughout this chain of islands, but much more is required before an accurate application of the Stokes theorem can be made. Certain geophysical data are very desirable and even necessary for the proper testing of long-range missiles. The author has repeatedly been

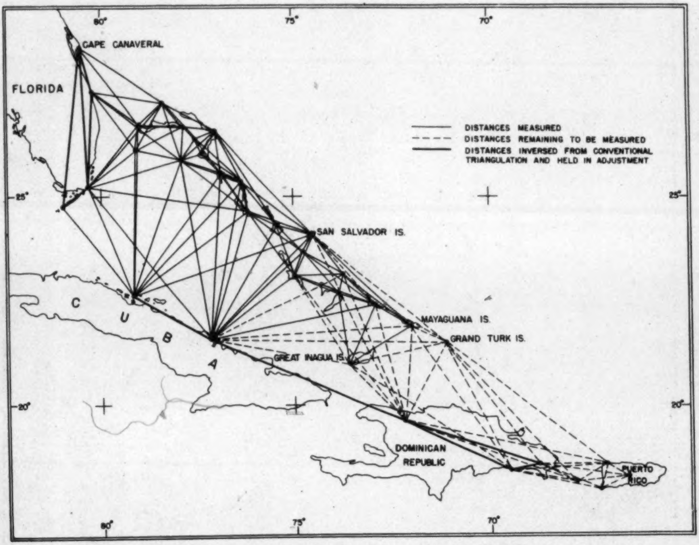
80°
75°
70°
CAPE CANAVERAL
FLORIDA
DISTANCES MEASURED
DISTANCES REMAINING TO BE MEASURED
DISTANCES INVERSED FROM CONVENTIONAL TRIANGULATION AND HELD IN ADJUSTMENT
25°
25°
SAN SALVADOR IS.
C
U
B
A
MAYAGUANA IS.
GRAND TURK IS.
GREAT INAGUA IS.
20°
20°
DOMINICAN REPUBLIC
PUERTO RICO
80°
75°
70°

Fig. 1--Shoran survey for Air Force Missile Test Center asked for an estimate of the magnitude and periodicity of the relative geoidal undulations lying within the range. The gravity-intensity survey required to provide this information with reasonable accuracy is a very large undertaking, and the time involved in the field work and computations is very great. Furthermore, the accuracy of gravity observations at sea has been questioned, and we are awaiting the development of newer and better instruments.

Meanwhile, in an attempt to provide an intelligent estimate of the geoidal undulations, the author decided to attempt to utilize the numerous deflections which can now be obtained by the astronomic geodetic method. By means of shoran trilateration we are for the first time obtaining geographic positions on the North American 1927 datum in the Bahama Islands area. Astronomic positions are also being observed at all shoran stations, and the resulting deflections of the vertical provide the most accurate geophysical data which have been obtained up to the present time in this region.

It seems reasonable to assume that the deflection angle represents the deviation of the geoid from the ellipsoid for some definite distance from a station. It also seems reasonable to conclude that the topographic corrections outweigh the isostatic corrections in the rugged topography which exists throughout the range. With these assumptions in mind, the author decided to test the use of deflections in the computation of the geoidal undulations. The data from which the computations are made are on the Clarke 1866 ellipsoid, and consequently the features will depart from the International ellipsoid. Nevertheless, they should give a reasonably accurate picture of the relative undulations.

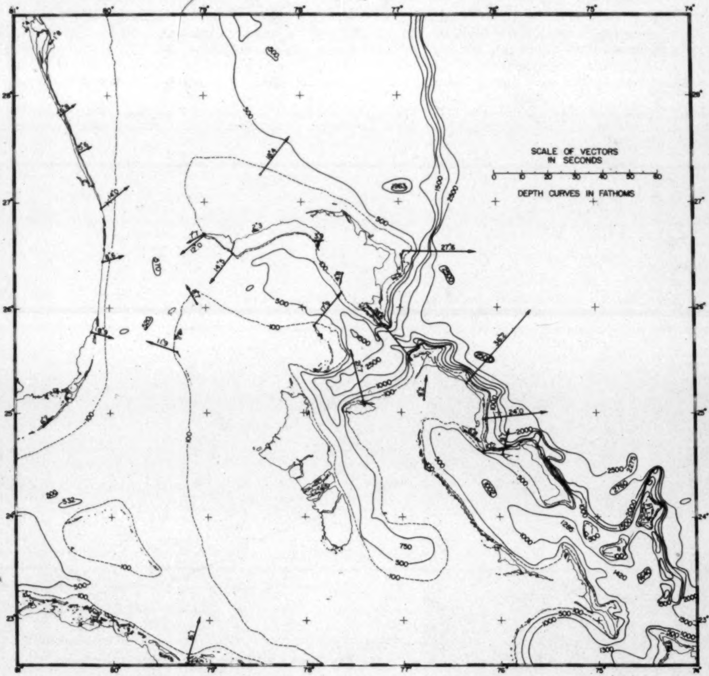

Fig. 2--Ocean topography of western Bahama Islands and deflections of the vertical

Correlation between topography and free-air anomalies--There is a marked correlation between the free-air gravity anomalies and the ocean-bottom topography in the Caribbean area. This correlation disappears only at considerable distances from the land areas where the effects of isostatic compensation begin to be felt. The correlation indicates that the topographic effect is large compared to the isostatic effect and probably demonstrates the regional nature of isostasy. The recent deflection observations confirm this fact by their relation to topography. Such deflections, strategically located, are of great assistance in developing the iso-anomaly curves. The topography of the first portion of the guided-missile range is shown in Figure 2. Also the deflections at present available are shown by vectors. The strong correlation between deflections and topography is immediately evident. If it were possible to determine deflections everywhere, we would obviously have the best means of obtaining geoidal undulations. However, at least at the present time, we are restricted to deflections on land.

In Figure 3, the existing free-air gravity anomalies are shown as well as the deflections. Obviously the iso-anomaly curves can be modified, in cases where insufficient gravity data exist, by properly located deflection data. A case in point is the entrance to Tongue of the Ocean, between Great Abaco and Eleuthera Islands. Normal curve-drawing techniques would not permit drawing the negative trough between the positive anomalies of +69 and +88 mgal on Great Abaco and Eleuthera Islands, respectively. However, the strong north-northwesterly deflections at New Providence Island and Great Egg Key clearly show that this trough exists throughout the length of the Tongue of the Ocean. Thus as more deflection information is gained, the curves can be further modified.

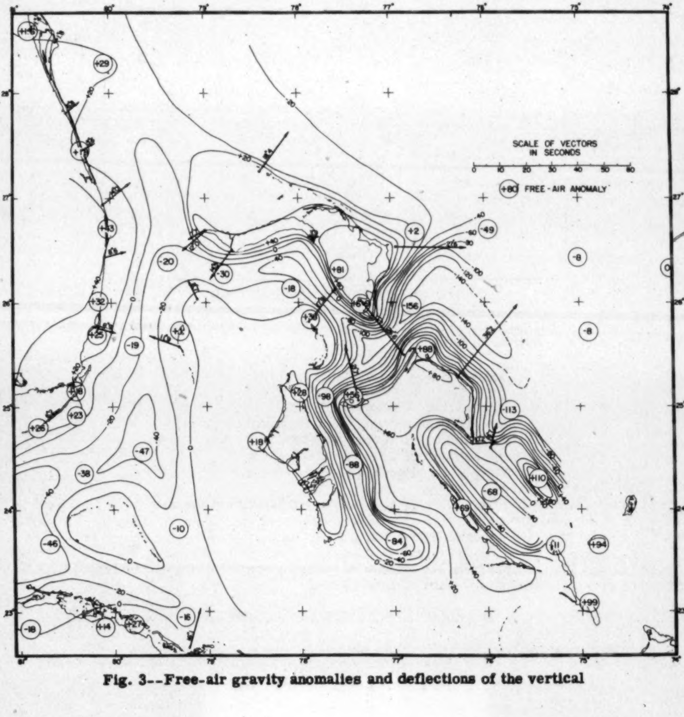

Fig. 3--Free-air gravity anomalies and deflections of the vertical

If a sufficient number of strategically located deflections are observed, it seems possible to compute relative geoidal undulations with considerable accuracy, providing the topography and existing observed anomalies are used as a guide in locating the deflection observations. The test computation which is described below might well be designated the "deflection-leveling method."

Deflection leveling--Of course, if deflection observations were established at close intervals all over the surface of the Earth, the progressive changes of the vertical outward from any given point accurately define the geoidal surface relative to the initial point. Over a water area, if isostasy is regional, it may be assumed that the slope of the geoid with respect to the ellipsoid will persist for some distance from the point of the deflection. If the bottom topography is uniform, with the deepest part of the ocean midway between two deflection points, a reasonable assumption is that the effect of each deflection extends halfway to the next point. When the bottom gradient is not uniform and the deepest portion is nearer one of the two stations, a more logical assumption is that the effect of each deflection extends as far as the deepest portion. Possibly a still more valid assumption would be to use templates divided into zones, similar to those used in isostatic reductions, for estimating the distance to which each deflection effect should be assumed to carry.

Closed loops can be formed from these links, and a least-squares adjustment can be made which will give some idea of the validity of the assumption. The method is essentially one of water leveling along a broken path.

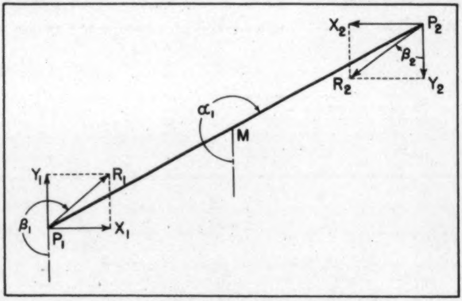

Fig. 4--Derivation of tilt formula

Derivation of tilt formula--The development of the method is illustrated in Figure 4. The quantities used are defined as follows.

X = deflection in the prime vertical
Y = deflection in the meridian
R = resultant deflection
D = distance between points in nautical miles
α = azimuth of the geodetic line
β = azimuth of a resultant deflection
ΔN = geoidal elevation change in meters

The deflection components X and Y are considered positive if the astronomic position is west and north of the geodetic position. Azimuths are measured clockwise from south. For convenience, the azimuth of the geodetic line is taken at the mid-point.

Let K be a factor expressing the amount of geoidal elevation change in meters produced by a tilt of one second of arc in one nautical mile. Then

$$K = (6080/3.2808) \tan 1'' = 0.008984$$

For the change in elevation from P_1 to M

$$\Delta N_1 = - D_1 K R_1 \cos(\alpha_1 - \beta_1)$$

Table 1--Deflection data

Station	Geodetic position		Deflections		Resultant
	Latitude	Longitude	Meridian	Prime vertical	
	° ′	° ′	″	″	″
Jupiter	26 56.9	80 04.9	+08.64	-11.01	14.00
Delray	26 26.8	80 04.4	+02.11	-08.30	8.56
Miami	25 46.5	80 11.7	-02.26	-08.65	8.94
Gun Cay	25 34.4	79 17.8	+04.70	+10.89	11.86
Isaac	26 01.7	79 05.3	+07.31	+04.75	8.72
Settlement Point Light	26 41.5	78 59.9	-07.28	+09.56	12.02
Pinder	26 30.3	78 45.9	-11.36	+09.00	14.49

Table 2--Azimuths and distances scaled from nautical charts

From	To	Azimuth	Distance
		°	naut mi
Jupiter	A	284.5	30.4
A	Settlement Point Light	284.5	30.4
Settlement Point Light	B	06.6	10.0
D	Isaac	06.6	30.0
Isaac	C	135.7	38.7
C	Jupiter	135.7	38.7
Settlement Point Light	G	310.4	08.4
G	Pinder	310.4	08.4
Pinder	H	31.3	09.9
H	Isaac	31.3	23.8
Isaac	D	115.0	29.6
D	Delray	115.0	29.6
Delray	E	177.5	14.9
E	Jupiter	177.5	14.9
Delray	F	256.0	29.8
F	Settlement Point Light	256.0	29.8
Delray	J	267.5	35.3
J	Pinder	267.5	35.3
Isaac	M	22.2	15.0
M	Gun Cay	22.2	15.0
Gun Cay	Q	141.3	24.4
Q	Delray	141.3	43.0
Gun Cay	N	103.8	18.0
N	Miami	103.8	32.4
Miami	L	190.0	20.5
L	Delray	190.0	20.5
Miami	K	256.0	31.1
K	Isaac	256.0	31.1

Table 3--Sample loop computation

Loop	Links			Deflection		Distance D	Azimuth α	Elev. diff. ΔN
	No.	From	To	X	Y			
				″	″	naut mi	°	m
2	- 5	Jupiter	C	-11.01	+8.64	38.7	315.7	-0.52
	- 6	C	Isaac	+ 3.86	+7.31	38.7	315.7	+2.76
	+ 7	Isaac	D	+ 3.86	+7.31	29.6	115.0	-1.75
	+ 8	D	Delray	- 8.29	+2.11	29.6	115.0	+1.76
	+ 9	Delray	E	- 8.29	+2.11	14.9	177.5	-0.23
	+10	E	Jupiter	-11.01	+8.64	14.9	177.5	-1.09
								+0.93

Formula $m = [-X \sin \alpha + y \cos \alpha] \times DK$

$K = 0.008984$

Equation $-(5) - (6) + (7) + (8) + (9) + (10) = +0.93$

Similarly from M to P_2

$$\Delta N_2 = - D_2 KR_2 \cos (\alpha_1 - \beta_2)$$

Since

$$R \cos \beta = - Y$$
$$R \sin \beta = X$$

Then

$$\Delta N_1 = D_1 K (Y_1 \cos \alpha_1 - X_1 \sin \alpha_1)$$
$$\Delta N_2 = D_2 K (Y_2 \cos \alpha_1 - X_2 \sin \alpha_1)$$

The data are shown in Tables 1 and 2, and a sample computation of a single loop is shown in Table 3. A sketch of the loops and links is shown in Figure 5. As in leveling, it is necessary to assume that the greater error will occur in the longer distances, and therefore the lines were weighted inversely as the length. Thus the longer lines will receive the greater corrections in the least-squares adjustment.

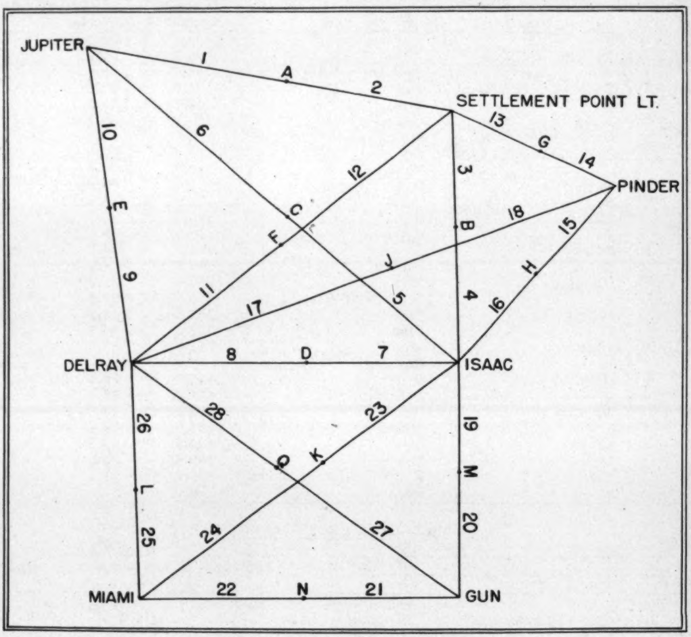
JUPITER
1
A
2
SETTLEMENT POINT LT.
13
G
14
PINDER
10
6
12
3
E
C
B
18
15
F
J
H
9
11
17
5
4
16
DELRAY
8
D
7
ISAAC
26
28
23
19
Q
K
M
L
25
24
27
20
MIAMI
22
N
21
GUN

Fig. 5--Sketch of loops and links

Examination of the sketch in Figure 5 will indicate that the condition equations shown in Table 3 can be set up based on closed loops.

Adjustment and results--Obviously, care must be taken to avoid identical equations. When an equation is set up which includes links, all of which have already been used in other equations, that equation is an identity, and if included in the solution will result in the first term of one of the divisors in the solution becoming zero or, in other words, in an indeterminate solution. There

Table 4--Condition equations

Loop or equation	Equations
1	$+(1)+(2)+(3)+(4)+(5)+(6)-1.44=0$
2	$-(5)-(6)+(7)+(8)+(9)+(10)+0.93=0$
3	$+(1)+(2)+(9)+(10)+(11)+(12)-2.28=0$
I_1	$+(3)+(4)+(7)+(8)-(11)-(12)+1.77=0$
4	$-(3)-(4)+(13)+(14)+(15)+(16)-1.20=0$
5	$+(7)+(8)+(15)+(16)+(17)+(18)+0.12=0$
I_2	$-(11)-(12)+(13)+(14)-(17)-(18)+0.45=0$
6	$-(7)-(8)+(23)+(24)+(25)+(26)+1.11=0$
7	$+(19)+(20)+(21)+(22)-(23)-(24)-0.18=0$
8	$+(21)+(22)+(25)+(26)+(27)+(28)+1.13=0$
I_3	$-(7)-(8)+(19)+(20)-(27)-(28)-0.20=0$

are three such identities shown by (I) in Table 4, leaving eight equations to be used in the solution. The solution was made by standard least-squares methods. The final v's and elevation differences as determined from the solution are also shown in Table 5. A check on the entire solution results from a summation of the final differences which must equal zero.

Following the determination of the adjusted differences, an arbitrary geoidal elevation of +1.30 meters was chosen for Jupiter, and the elevations of all other stations relative to Jupiter were determined by application of the adjusted differences. The geoidal elevation of Jupiter was

Table 5--Adjusted differences

Links			Obs. diff. ΔN	v	Adj. diff.
No.	From	To			
(V)			m	m	m
+ 1	Jupiter	A	-2.32	+0.54	-1.78
+ 2	A	Settlement Point Light	+2.03	+0.55	+2.58
+ 3	Settlement Point Light	B	-0.75	-0.15	-0.90
+ 4	B	Isaac	+1.84	-0.43	+1.41
+ 5	Isaac	C	-2.76	+0.46	-2.30
+ 6	C	Jupiter	+0.52	+0.47	+0.99
+ 7	Isaac	D	-1.75	-0.08	-1.83
+ 8	D	Delray	+1.76	-0.08	+1.68
+ 9	Delray	E	-0.23	+0.08	-0.15
+10	E	Jupiter	-1.09	+0.08	-1.01
+11	F	Delray	+2.29	+0.52	+2.81
+12	Settlement Point Light	F	-2.96	+0.51	-2.45
+13	Settlement Point Light	G	+0.19	+0.13	+0.32
+14	G	Pinder	-0.04	+0.13	+0.09
+15	Pinder	H	-1.16	+0.10	-1.06
+16	H	Isaac	+0.90	+0.26	+1.16
+17	Delray	J	-2.65	-0.16	-2.81
+18	J	Pinder	+3.02	-0.16	+2.86
+19	Isaac	M	+0.72	-0.06	+0.66
+20	M	Gun Cay	+0.03	-0.05	-0.02
+21	Gun Cay	N	-1.89	-0.11	-2.00
+22	N	Miami	+2.60	-0.20	+2.40
+23	Isaac	K	-0.55	-0.30	-0.85
+24	K	Miami	+2.19	-0.30	+1.89
+25	Miami	L	+0.13	-0.33	-0.20
+26	L	Delray	-0.65	-0.34	-0.99
+27	Q	Gun Cay	+2.30	-0.05	+2.25
+28	Delray	Q	-1.36	-0.10	-1.46
		Means	1.45	0.24	1.46

$$PE = \pm 0.6745 \sqrt{\Sigma V^2/(n-1)} = \pm 0.20$$

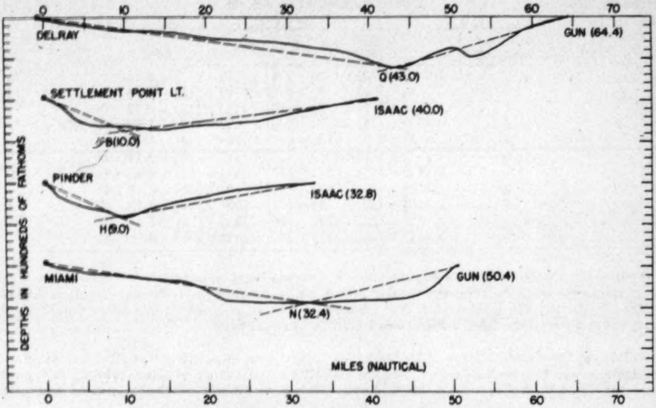

Fig. 6--Distribution of deflection-gradient effect on lines where deepest water is not at mid-point

chosen as +1.30 because a rough computation indicates that Jupiter is probably about 1.3 meters above Cape Canaveral, the assumed zero point. Therefore, all computed geoidal heights are relative to Cape Canaveral.

Figure 6 illustrates the method used to apportion the deflection effects insofar as distances from the stations were concerned. On all other lines the effect was assumed to carry to the mid-point of the line.

Table 6--Improved closing errors when ocean bottom topography is used as guide in computing deflection effect

Loop	Link affected	Distances		Closures	
		Computed to mid-point	Computed to deepest point	Assumption A	Assumption B
		naut mi	naut mi	m	m
1	3	20	10	. . . .	. . . .
	4	20	30	-2.81	-1.44
I_1	3	20	10	. . . .	. . . .
	4	20	30	+0.40	+1.77
4	3	20	10	. . . .	. . . .
	4	20	30	. . . .	. . . .
	15	16.7	9	. . . .	. . . .
	16	16.7	24.4	-1.10	-1.20
5	15	16.7	9	. . . .	. . . .
	16	16.7	24.4	-1.15	+0.12
7	21	25.2	18.0	. . . .	. . . .
	22	25.2	32.4	-1.51	-0.18
8	21	25.2	18.0	. . . .	. . . .
	22	25.2	32.4	. . . .	. . . .
	27	38.7	24.4	. . . .	. . . .
	28	38.7	43.0	+0.97	+1.13
I_3	27	38.7	24.4	. . . .	. . . .
	28	38.7	24.4	-1.37	-0.20
			Means	1.33	0.86

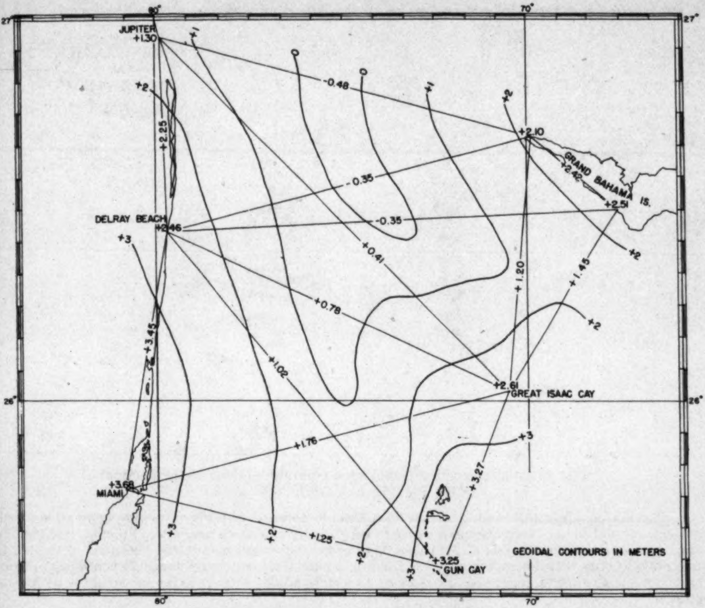
80°
70°
27°
27°
JUPITER
+1.30
+1
0
-0.48
0
+1
+2
+2
+2.10
GRAND BAHAMA IS.
+2.42
+2.51
+2
+2.25
-0.35
DELRAY BEACH
+2.46
-0.35
+0.41
+3
+1.20
+1.45
+0.78
+2
+3.45
+1.02
+2.61
GREAT ISAAC CAY
26°
26°
+1.76
+3
+3.27
+3.68
MIAMI
+3
+2
+1.25
+2
+3
+3.25
GUN CAY
GEOIDAL CONTOURS IN METERS
80°
70°

Fig. 7--Relative geoidal heights computed from deflections of the vertical

The geoidal undulations are shown in Figure 7 as one-meter contours. The computation was first made with all deflection effects computed to the mid-point of the line. When compared with the results as obtained when bottom topography was considered, two effects were noted: (1) The closures were improved on the affected lines as shown in Table 6. (2) The general location of the one-meter geoidal contours remained almost unchanged.

As seen from the data in Table 5, the average elevation difference is 1.46 ± 0.20 meters. The ratio of the probable error to the average difference is about one to seven, indicating that the results may represent real values.

Encouraged by the apparent consistency of the test computation, two additional adjustments were made. The first one included only certain deflection observations of the U. S. Coast and Geodetic Survey in Florida. The second included the stations in the test computation plus several additional deflections in the Bahama Islands. The resulting geoidal undulations are shown in Figure 8. Common points in these two adjustments are shown in Table 7. Obviously on several lines the assumption that the deflection effects carry as far as the mid-point of the line is not valid and more deflection observations are required. Yet even in these equations the average closing error in each loop was only 0.8 meter, and the ratio of the average corrections to the average computed difference was 1 to 5.

Table 7--Common points in the Florida and Bahama Islands data

Station	Geoidal heights	
	Florida mainland computation	Bahama Islands computation
	m	m
Jupiter	+1.2	+1.3
Delray	+2.7	+2.5
Miami	+4.3	+3.7

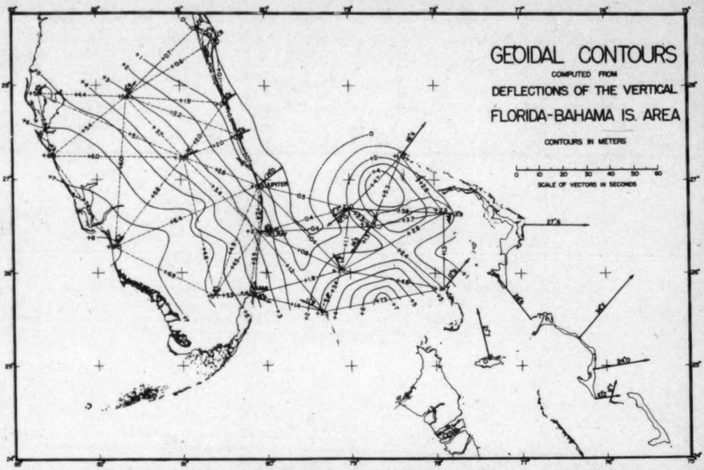

Fig. 8--Geoidal contours computed from deflections of the vertical in the Florida-Bahama Islands area

Conclusion--It is interesting to note that Tanni's solution of the world-wide undulations indicates a geoidal rise of three meters between the vicinity of Cape Canaveral, Florida, and the ocean area east of the southern part of Florida. This is the value obtained in the solution. It is also interesting to note that the values at the deflection points will remain unchanged even though different assumptions are made regarding the manner in which the deflection varies between the deflection points.

A possible further refinement would be to assume curved surfaces with zero deflections of the vertical at the points of maximum or minimum geoid height. If this were done the highs and lows obtained in the above solution would be reduced.

Rice has suggested that the deflection varies linearly with distance from one station to the next one. A test of this on the line from Jupiter to Set reduces the low between these two deflection points to about one-half of the amount obtained in this solution, but the same difference of geoid height between Jupiter and Set is obtained. When the deflection is the same in magnitude and direction at each of the two stations, either assumption will give the same result at intermediate points. When the deflections are of opposite signs so that there is an elevation or depression between the stations, the results obtained from the two assumptions are somewhat different for intermediate points. There is no assurance at this time which assumption most nearly approximates the truth. However, within a few months it will be possible to compare the results obtained above with a new solution wherein a number of additional deflections have been observed within the same area. Some indication of the validity of the assumptions should be derived.

With the amount of data available at this time it is believed that no further refinement is justified. Obviously a greater number of deflections are desirable, and an astronomic party is now in the field obtaining them. Certainly an analysis of this nature will at least outline the approximate locations of the principal features. That was the objective of the writer in making this investigation. The results should be valuable supplementing the computations made by the Stokes method.

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THE GEOPHYSICAL APPLICATIONS OF GRAVITY ANOMALIES

W. Heiskanen

Abstract--The gravity anomalies are an important tool in the hands of the geodesists and geophysicists. For instance, the positive Bouguer anomalies of the oceans and the negative ones of the mountains show qualitatively that isostatic equilibrium exists in broad lines. The isostatic anomalies are even able to localize the isostatically compensating layers and in such a way to determine the thickness of the Earth's crust. Also local disturbing masses of different types are not too difficult to discover. With the rapid and accurate gravimeters beginning a new epoch in gravimetry, quite new views for detailed geophysical study of the behavior of the Earth's interior are to be presented. But the gravity anomalies must be used carefully. In some cases they too easily lead us to wrong conclusions.

In 1951, I had the privilege of addressing American geodesists and geophysicists at the Annual Meeting of the American Geophysical Union about the geodetic applications of the gravity anomalies [HEISKANEN, 1951]. Now I am glad to have the opportunity to tell you something about the geophysical applications of the same gravity anomalies.

As the science of gravimetry is partly geodetic and partly geophysical, it allows us to compute the shape of the geoid and also suggests the reasons which cause the irregular shape of the geoid. The only tools which the gravimetrist has are the gravity anomalies, Δg. Supposing that we use the most suitable gravity formula in computing the gravity anomalies, the only cause for the remaining residual anomalies are the regional or local disturbing masses at various distances from the gravity station. In geophysical applications we have to try to localize these disturbing masses by the aid of the gravity anomalies which they cause. This is a difficult problem because, theoretically speaking, the disturbing masses can be distributed in the Earth's interior in infinitely many ways and nevertheless cause the same gravity anomaly at the gravity station.

In using not only one station but many stations on a given area, and considering the geological facts and seismological conclusions, we can pretty well localize the disturbing masses.

As every geophysicist knows, the Bouguer gravity anomalies have been much used for local geophysical purposes. Very well known are the so-called "density profiles" which the exploration geophysicists use in obtaining the most plausible density value of the studied area. Using this, the Bouguer gravity anomalies are computed using different density values. Generally, these anomalies are dependent on the elevation of the station and the area. The density value which most nearly eliminates the elevation term of the gravity anomalies is thought to be the best.

The Bouguer anomalies can be used also for general geophysical studies. The fact that the Bouguer gravity anomalies are increasing large negative values, the higher the mountains, is already evidence for isostatic equilibrium. Still more striking evidence for isostatic principles is given by the oceans. There the free-air gravity anomalies are practically the same as those on the continents at the same latitude in spite of the low density of the ocean water. Also, if we compute the Bouguer anomalies for the oceans, that is, if we consider the ocean basins to be filled with additional material so that the density of the ocean basin would be the same as the density of the Earth's crust, we get strongly positive gravity anomalies.

The Bouguer anomalies can therefore show qualitatively that isostatic equilibrium prevails. However, we can not use these anomalies for quantitative investigation. Only in a few cases are the Bouguer anomalies able to show how complete the isostatic equilibrium is, how great the depth of compensation is, what the thickness of the Earth's crust is, and whether the compensation is local or regional. All these questions can be studied better by means of the isostatic anomalies.

The Bouguer gravity anomalies can also be misleading now and then when they are used for general geophysical studies. This is particularly the case in the "Randsenken" of mountain chains and still more so at the oceanic margins and in the ocean islands. This is due to the fact that the isostatic compensation has a remarkable effect on those gravity anomalies very far in the horizontal direction from the root formations themselves. For instance, in the "Randsenke" of the Alps the isostatic effect of the Alps is of the order -50 to -80 mgal. When trying to explain the anomalies in terms of disturbing masses by the aid of the density profile of the Bouguer anomalies, we can "bark up the wrong tree." We think the disturbing layer to be near the Earth's surface, whereas the root formations of the neighboring mountains or the antiroots under the surrounding oceans are the real reason for the anomalies.

I think that this is one reason why Vening Meinesz and Woollard came to different results concerning the density of the Earth's crust in the Hawaiian area. According to Vening Meinesz, the density of this area is about 3.0; according to Woollard, only 2.3. In this particular case we can not use the Bouguer anomalies. If isostatic equilibrium prevails, they are, of course, smaller positive values for the ocean islands than for the neighboring oceans. As we know, the Bouguer anomalies are positive over oceans running up to +300 mgal or more; over ocean shelves and on coastal plains they are nearly zero, and in mountainous areas they are strongly negative. This must be so because isostatic equilibrium prevails in broad lines.

The following example explains this. The top of an ocean island cone rises from the bottom of an ocean of 5000-m depth to 2000 m above sea-level. The shore line is taken to be at a distance of 58.8 km (boundary between the zones M and N). The edge of the slope is taken to be at the distance of 166.7 km (outer radius of the zone 0), at a depth of 5000 m. If the isostatic equilibrium is complete and the thickness of the Earth's crust is assumed to be 30 and 40 km, the Bouguer anomalies are as indicated in Table 1.

Table 1--The Bouguer anomalies on a circular ocean island cone and in its vicinity if isostatic equilibrium prevails[a]

Location	Distance from center of island	Elevation	Bouguer anomalies	
			T = 30 km	T = 40 km
	km	m	mgal	mgal
	0	2000	+ 16	+ 48
	14.7	1500	+ 16	+ 53
	29.4	1000	+ 32	+ 64
	44.1	500	+ 59	+ 86
Shore line	58.8	0	+ 78	+102
	80.4	-1000	+123	+140
	102.0	-2000	+176	+188
	123.6	-3000	+216	+219
	145.2	-4000	+246	+232
Edge of slope	166.7	-5000	+302	+290
	267	-5000	+332	+327

[a] This example has been computed by Kasim Yasar. The effect of the zones 10 to 1 has been omitted because it is dependent on the location of our "island."

We see that all Bouguer anomalies are positive. They are gradually increasing from +16 mgal (resp. +48 mgal) to about +330 mgal. At the shore line they are +78 and +102 mgal, at the edge of the slope +302 and +290 mgal, and 100 km farther from the shore line +332 and +327 mgal. Still farther from the island they increase slowly and reach the value +340 mgal, according to both assumptions.

The Bouguer anomalies on the island are small because the negative effect of the root of the island compensates for most of the positive effect of the antiroot of the ocean. This example shows that the Bouguer anomalies can not be used to explain the detailed structure of the Earth's crust under the ocean island.

In geophysical literature only small attention has been paid to the gravimetric method for determining the thickness of the Earth's crust, although it seems to give accurate results. Therefore, it might be worth while to explain this matter. As already mentioned, the Bouguer gravity anomalies are strongly negative in mountainous areas, while the free-air anomalies are generally positive. Thus, it is a good idea to develop the gravity anomalies according to the different assumptions as a function of the elevation of the station, in the form $\Delta g = a + b \times H$, where a and b are coefficients obtained from the gravity material and H is the elevation of the station.

In order not to be misunderstood, I would like to mention that the free-air reduction is, in fact, an isostatic reduction with the thickness $T = 0$, and the Bouguer reduction also can be thought of as an isostatic reduction, with $T = \infty$.

By choosing such values for T as to make the elevation term zero, that is, the coefficient b equals zero, we get a good estimate of the thickness of the Earth's crust. As Table 2 shows, we get in this way as the normal thickness of the Earth's crust in Norway 32 km (37 km for h = 1000 m, where h is the elevation of the terrain); in the Ferghana Basin 38 km (49 km for h = 2000 m); in the Central Alps 20 km (31 km for h = 2000 m); in the West Carpathians 30 km (34 km for h = 800 m); in North Italy 29 km (40 km for h = 2000 m); and in South Africa 30 km (41 km for h = 2000 m).

Table 2--The gravity anomalies Δg (according to free-air, Bouguer, and isostatic Airy-Heiskanen reductions) as a function of the observation height H (unit of Δg = 1 mgal, of H = 1000 m)

T^a	Δg					r^b
	Norway [Heiskanen, 1926]	Central Alps [Holopainen, 1947]	Northeast Italy [Morelli, 1951]	Ferghana Basin[c] [Erola, 1951]	West Carpathians [Tanni, 1942]	South Africa [Hales and Gough, 1950]
km	mgal	mgal	mgal	mgal	mgal	
0	-6 + 38 H	-137 + 60 H	-58 + 39 H	-138 + 16 H	13 + 14 H	0.275
20	....	- 2 H	38 + 9 H	-71 + 14 H	....	0.049
30	....	1 - 11 H	40 - H	-59 + 7 H	28 + 0 × H	-0.002
40	20 - 8 H	- 17 H	40 - 8 H	-51 - H	....	-0.026
60	21 - 20 H	-6 - 23 H	37 - 18 H	-38 - 12 H	34 - 23 H	-0.063
80	18 - 18 H	....	....	-31 - 20 H	....	.....
100	14 - 35 H	....	....	-26 - 27 H	....	.....
∞	-3 - 80 H	-85 - 39 H	-36 - 43 H	-138 - 87 H	8 - 53 H	-0.900

[a] T denotes the normal thickness of the Earth's crust corresponding to zero elevation.

[b] In middle Asia.

[c] Values of r, the correlation coefficient between the anomalies and station heights. The smaller the value of r, the better is the assumption.

These values of the thickness of the Earth's crust correspond to zero elevation. The values in parenthesis, 37 km, 49 km, etc., correspond to the elevation indicated. The thickness of the Earth's crust, T_c for continents, T_s for oceans, is of course, the greater under the continents the higher the elevation and the smaller under the oceans the deeper the ocean. It is a function of the topography. We get

$$T_c = T + \frac{\delta + \delta'}{\delta'} h$$

and

$$T_s = T - \frac{\delta + \delta' - \delta''}{\delta'} t$$

where δ is the density of the Earth's crust, δ' the density difference between the substratum and crust, $\delta'' = 1.03$, the density of the sea water, and t the depth of the ocean. For the values $\delta = 2.67$; $\delta' = 0.6$; $\delta'' = 1.03$; $T = 25$ km, $h = 2$ km, and $t = 5$ km, we get $T_c = 35.9$ km and $T_s = 6.3$ km. The thickness of the root itself is in this case 8.9 km, and the thickness of the "antiroot" is 13.7 km.

According to the recent opinion of the seismologists (among others, Gutenberg), the crust is formed in the continents by a layer of sialic rock with thickness of ten km. Below this down to the Mohorovicic discontinuity at a depth between 30 and 40 km, but deeper, at least under some mountain areas, are simatic rocks, the density of which is a little higher than the density of the first layer. Below the Mohorovicic discontinuity begins the ultra-simatic material; in other words, the substratum into which the root formations have sunk. Under the oceans the depth of the Mohorovicic discontinuity is remarkably smaller than under the continents. Under the Pacific basin the ultra-simatic material ought to begin at a depth of five km below the surface.

According to GUTENBERG [1951], the most distinct discontinuity close to the Earth's surface, namely, the Mohorovicic discontinuity, is at a depth of 27-30 km under Heligoland, 30 km under the Black Forest in Germany, 36 km under the Canadian Shield, 33 km in New England, 42 km near Washington, D. C., and 40 km in California.

If we think that this Mohorovicic discontinuity means the under boundary of the lighter density Earth's crust, the agreement between the gravimetrically computed and seismologically obtained values is excellent.

The agreement is also complete in that the isostatic floating theory presumes that under the mountains must be root formations; under the oceans, antiroots. Seismologically the root formations have been realized to be at least under the Alps and the Sierra Nevada.

In several of my publications I have pointed out that the isostatic floating theory can explain most of the gravity anomalies, but not all of them. The general root theory [HEISKANEN, 1950] seems to explain more. According to this theory, the topography is only one reason for the root formations, but there can be root formations without any mountains, as, for example, the Vening Meinesz strips of negative gravity anomalies show. There also exist mountains so small, as, for instance, the Harz mountain in Germany, that only small if any root formations exist.

The isostatic equilibrium is not everywhere complete. In general, about ten per cent of the large gravity anomalies of the oceans and of the high mountains, and in some cases more than 50 per cent, have to be explained in some other way. We can say that isostatic equilibrium prevails in broad lines. The world-wide formations such as oceans and high mountains have already reached this stage nearly completely. On the other hand, many interesting areas of the world are at least not in complete isostatic equilibrium. Many ocean islands, belts of negative gravity anomalies, and Fenoscandia are good examples of such regions. There exist also those small formations that they will never reach this ideal stage.

The exceptional areas are, of course, most fruitful for scientific study. Many such areas are now covered with so many gravity stations that detailed local investigation concerning the degree of isostatic equilibrium is possible. There exist various reasons which bring about deviations from the equilibrium. Post-glacial restoration, subcrustal convection currents, chemical and thermal processes, tectonic movements, sedimentation, erosion, and the strength of the crust are such reasons.

It is well known that there exist large areas where the gravity anomalies are either systematically positive or systematically negative, even after the isostatic corrections. Most parts of

Europe and large areas of the North Atlantic are regions of positive gravity anomalies. In the same way, large parts of India are areas of negative gravity anomalies. What might be the reason for these remarkable deviations from equilibrium? If the Earth's crust were able to support such large systematic mass anomalies, that is, if the disturbing masses were not isostatically compensated, the thickness of the disturbing layer would be only about 160 m. In this case the disturbing layer could be close to the Earth's surface. If we assume that the Earth's crust can not carry such big mass anomalies, we must think that the disturbing masses are compensated. Assuming this, we come to the conclusion that these layers which could explain the systematic positive and negative gravity anomaly areas ought to be very deep, according to several studies at depths of 500 to 600 km.

We can therefore conclude that the greater part of the topographic masses are compensated for at a depth of 30 to 40 km, but a small part of the disturbing layers which bring about the residual one-sign gravity anomaly areas is obviously compensated at very great depths.

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THE LENGTH OF IONIZED METEOR TRAILS

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Abstract--The length of meteor ionization columns is defined as the maximum possible separation of points along the trail from which normal-incidence radio reflections may be obtained, when a radio system of prescribed characteristics is used. A statistical method is employed to determine the relative frequency of trails of different lengths from simultaneous measurements made at two similar 23-megacycle meteor detection stations 100 km apart. For sixth magnitude meteors, a mean trail length of 25 or 30 km is obtained.

In recent years, the study of meteors and of their behavior in the upper atmosphere has received a considerable impetus through the use of radio-detection techniques. It has been discovered that a meteor leaves a linear trail of ionized gas in its path as it vaporizes in the region 80 to 120 km high. If a high-frequency radio signal is incident upon this line of ionization from such a direction that the transmitted ray meets the trail in a right angle, a strong reflected signal will result. At a radio frequency of 23 mc/sec, the duration of such echoes is commonly of the order of one second, but it exhibits wide variation.

The signal returned from a meteoric ionization column during its formation increases rapidly in intensity until that portion of the trail which is nearest the observer (the perpendicular point) has been formed. Thereafter normal processes of decay cause the intensity gradually to decline. It has been shown that the change in effective distance of the reflection point during trail formation, most accurately measured by the Doppler effect, is an accurate indication of the speed of the meteoric particle [MANNING, VILLARD, and PETERSON, 1949]. A residual Doppler frequency shift, noted after the trail is completely formed, has also been discovered, and the drift velocity of the trail caused by upper-atmosphere winds can be measured with the aid of this "body-Doppler" [MANNING, VILLARD, and PETERSON, 1950].

Of all the properties of meteoric ionization columns, perhaps the most fundamental to an understanding of meteoric ionization phenomena is the shape of the trail. Evidence from a variety of sources now suggests that the ionization cylinders are typically no more than a few meters in effective diameter at a radio frequency of 23 mc/sec. For instance, study of the body-Doppler caused by wind drifts shows no observable superimposed component caused by trail expansion or contraction. Again, polarization and signal-strength measurements of the reflected-wave vectors can be best interpreted in terms of a small but expanding column.

The length of the ionized trails, on the other hand, has not been systematically studied. Some idea of trail length has been obtained in certain cases by multiplying the particle velocity by the time taken for trail formation, that is, the elapsed time from the commencement of the echo signal to the end of the diffraction fluctuation, or up-whistle. Such a study is complicated, however, by the greatly reduced scattering cross section presented by the trail during the early stages of its formation, when the perpendicular reflection condition has not yet been achieved. Since the echo may not be detected until an appreciable portion of the ion column has been formed, the apparent trail length determined in this way will often be less than the true length.

The ideal method of length determination would be one in which observing stations were distributed continuously over the surface of the Earth, so that stations could always be found whose rays were normal to the ionization column at its two ends. The separation of the reflection points would then be a true measure of the length of the trail. The experiment to be described enables a determination of trail length to be made in much this manner, but requires the use of only two receiving stations.

Definition of trail length--It is necessary to define the length of an ionization column with some care. Theory indicates that the density of ionization along the trail will be a continuous function, zero outside the atmosphere and exponentially increasing toward a maximum value as the meteor enters the more resisting air of lower altitudes. The peak ionization occurs at a height somewhere between 80 and 120 km, and is quickly followed by complete vaporization of the meteor. For practical purposes, we shall say that the ionization column exists at a given point whenever it is capable of returning a detectable signal with the incident ray normal to the trail at that point. In terms of diffraction theory, the above definition means that a trail is said to exist at a certain point if the first Fresnel zone for reflection of a spherical wave be centered at that point, and is capable of returning a detectable signal. The definition of trail length just given is clearly dependent upon the radio system gain, the distance of the meteor from the station, and the operating frequency. In principle, it can be related to other bases of definition such as the length of trail over which the ionization per unit length exceeds an arbitrary value.

The magnitudes of the meteors producing trails may be estimated by the usual methods, that is, by counting their rate of arrival and comparing this with previous estimates of rate of particle incidence versus size.

The method to be used in determining trail lengths depends upon the existence of a perpendicular relationship between the meteor trail and the ray from the observatory at a time corresponding to the maximum of the received field strength. Such a relation obviously holds in the case of a long uniform cylinder of ionization of small diameter, since the maximum received field will be detected at the time when the first Fresnel zone has just been formed. The center of the first Fresnel zone is located at the perpendicular point on the trail. In the case of a few large meteors, the elementary scattering coefficient is not uniform along the trail, and the received field strength may reach a maximum appreciably later than the arrival of the meteor at the perpendicular point. A number of examples of such complex echoes have been described by MILLMAN and McKINLEY [1948, 1949; also McKINLEY and MILLMAN, 1949], with the aid of a range-time presentation. An effort must be made to exclude such echoes in a study of the present type.

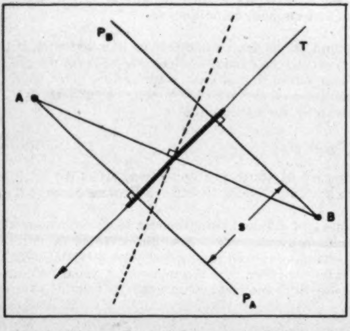

Fig. 1--Planes P_A and P_B contain Stations A and B, and are perpendicular to the trail T; to obtain echoes at both A and B, P_A and P_B must strike ionized part of trail

Geometry of coincident detection--Let there be two complete transmitting and receiving stations A and B, separated by a distance comparable with the height at which the echoes originate. A meteor establishing a trail T, as in Figure 1, will be detected at the stations A and B, if the plans P_A and P_B perpendicular to the trail T pass through A and B and cut T along that portion of the trail where adequate ionization density exists [MANNING, 1948]. For trails which are perpendicular to the site-line AB, planes P_A and P_B become one, and all meteors detected at one station will be detected at the other. If, however, the trail T meets line AB in less than a right angle, planes P_A and P_B will intersect T at separate points. If the angle is sufficiently small, the separation may exceed the length of the ionization column, and detection will be possible at not more than one station. Coincident detection is thus seen to be dependent upon the effective trail length and upon the radiant of the meteor, since the radiant determines T as a vector. In addition, if coincidence is to be obtained, the meteor must enter the atmosphere in a horizontally restricted region in order that the planes P will not strike the trail T above or below the ionized segment. Because of the number of conditions prerequisite to coincident detection, a very small fraction of the meteors detected at one location can also be detected at the other.

When a coincidence is observed at both stations, the two echoes will not in general be detected at the same instant. In the case of Figure 1, the echo at station B would be detected first, and that at Station A at a later time determined by the separation of planes P_A and P_B and by the meteor velocity. If the transmitters were of sufficient power, a meteor whistle or perhaps a head echo would be detected at both stations at the initial instant of column formation, but in any case the maximum signal strength would not be observed until the first Fresnel zone corresponding to the station in question had been created. There would therefore be a difference in the times at which the peak amplitudes were observed, which would be a measure of the separation of the reflection points on the trail. In the case of any coincident detection, it is thus possible to give a lower bound for the effective trail length.

In addition to the "true" coincidences which result from the detection of a single meteor trail at two locations, "random" coincidences will be detected experimentally. Since truly coincident echoes do not appear at identically the same time at both receivers, timing is not a conclusive proof that two received echoes result from the same trail. The possibility remains that by chance two quite independent meteors were detected, each only at a single station. There is no adequate method for differentiating such random coincidences from true coincidences in all individual cases. Therefore, methods must be devised to separate them statistically when analyzing the data.

The Stanford-Turlock observations--A test of the possibility of studying meteor trails coincidently at isolated stations was performed on the nights of September 23 and 24, 1949, with stations at Searsville Lake, bounding the Stanford grounds, and in the vicinity of Turlock, California. The station at Turlock was located just 100 km due east of the Stanford station. At both stations continuous-wave Doppler equipments were used, with power outputs in the neighborhood of a kilowatt, a transmitted frequency of 23.1 mc/sec, and dipole antennas one-quarter wavelength above ground. The system sensitivities were very nearly equal. The echo amplitudes were recorded on paper tape with the aid of direct-writing oscillographs. In reducing the data, only those echoes were retained which displayed an amplitude-time characteristic typical of perpendicular reflection. With this type of echo, time of occurrence may be measured accurately. All complex echoes were excluded, a step which may have introduced some bias in favor of the smaller meteors. In all, 72 pct of the meteors detected, or a total of 1790 meteors from the Stanford records and 1773 meteors from the Turlock records, were retained during the five hours and 21 minutes of recording. Whenever echoes were received on the two systems with starting times differing by one second or less, an "apparent" coincidence was recorded. The apparent coincidences are equal in number to the sum of the true and random coincidences.

Isolation of true coincidences--The expected number of true coincidences can be found, if the number of random coincidences is known, by subtracting the random coincidences from the apparent coincidences. If the number of meteor traces occurring at both stations in a given time interval t is recorded, and if it is assumed that the time of arrival of a meteor is random, the expected number of random coincidences C_r is given by the expression

$$C_r = 2N_A N_B \Delta t/t \qquad (1)$$

where N_A and N_B are the numbers of meteors detected at stations A and B, and Δt is the maximum time interval between echo starting times for which a coincidence is defined to have occurred.

An alternative method of determining the number of random coincidences is to determine the number of apparent coincidences with relative times of appearance not within Δt seconds, but between say $T - \Delta t$ and $T + \Delta t$, where T is at least several seconds (displaced-tape method). With this disparity in time, true coincidences would not be expected, and the number of apparent coincidences equals the number of random coincidences. Both methods were used, and yielded very nearly the same result.

It was found that 73 meteors, or approximately one out of every 24 of those which produced an echo at one station, also produced an echo at the other. Echoes whose starting times were displaced more than 0.4 sec were found to be probably not caused by the same meteor, while 25 to 45 pct of meteors with smaller displacements could be considered to be coincident.

In Figure 2, the number of apparent coincidences obtained during the tests is plotted as a function of the measured differences in starting times of the echoes. The average number of random coincidences as computed by the displaced-tape method is also shown in the diagram. Although a certain amount of scatter exists in the plot because the sample size is finite, it is easily seen that for small time differentials there is a definite increase in the number of apparent coincidences in excess of the number of random coincidences. This excess, which represents the true coincidences, is plotted in Figure 3. In this plot the points from the data of September 23 and 24 have been plotted independently, and a most probable smooth curve fitted through the points. In fitting the curve, use was made of the theoretical result of the next section to the effect that a negative curvature is not allowable. The ordinate scale was then converted to represent the relative probability of coincident detection, with unity chosen for the highest point of the curve (for zero difference in starting time).

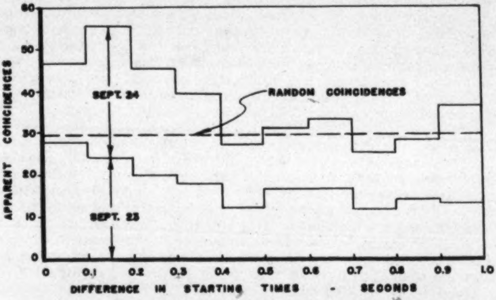

Fig. 2--The number of apparent coincidences between the Stanford and the Turlock records as a function of the difference in time of appearance

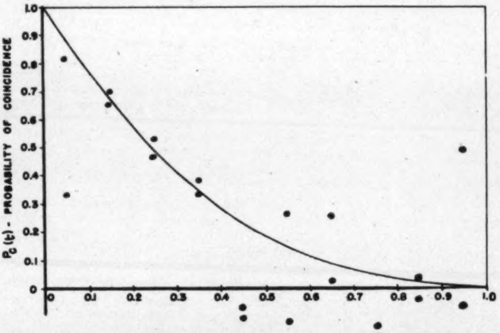

Fig. 3--The experimental relative probability that an echo detected at Station A will be accompanied by an echo at Station B, versus the difference in starting time t = s/V

The only feasible way to reduce the scatter in the true-coincidence curve is to increase the term of observation. The per cent scatter will vary inversely with the square root of the interval of observation. Although more coincidences will be detected if the system sensitivity is increased, no decrease in the scatter will be obtained. This result follows because the number of true coincidences is directly proportional to the rate of detection (N/t), while from Eq. (1) the number of random coincidences depends upon the square of the rate of detection. The random fluctuations, in the curve of number of random coincidences versus time difference, are then proportional directly to the rate (N/t). Increasing the rate increases the random fluctuations in the apparent coincidence curve (resulting from the random coincidences) in direct proportion to the increase in the true coincidence component of the apparent coincidence curve. Increasing the rate does not improve the accuracy. Reducing the station separation AB would increase the fraction of true coincidences, and so the accuracy, but spacings of less than the 100 km between the Stanford and Turlock stations would not be permissible, since trail lengths of an appreciable fraction of this spacing are found to occur.

Interpretation in terms of trail lengths--Figure 3 gives the relative probability that a given meteor can be detected at two receiving stations as a function, not of the separation on the trail of the reflection points but of the time interval required for a meteor to travel the distance represented by the separation. If the velocities of the individual meteors had been known, the separations could have been computed. Not having the velocities, one may assume that all meteors were traveling with some typical mean velocity, say 50 km/sec. The abscissas of Figure 3 may then be interpreted in terms of trail length, and although the curve of coincident probability versus separation obtained in this way exhibits a slightly greater spread than the true curve, it maintains its essential characteristics.

Three factors serve to determine the probability of coincident detection of an arbitrary trail at two locations. The first is the relative probability that two randomly placed rays separated by a distance s will both strike a trail of length L, as shown in Figure 1. If detection is assumed to occur at one station, the probability that the second ray will strike the trail within L is (L - s)/L. The second factor is the relative frequency of occurrence of trails of various lengths. This frequency may be determined from the number N(L) of trails of length L in a given sample. The third factor governing the experimental rate of coincidence is the relative number of meteors with radiants in such positions that they can produce echoes of given reflection point spacing s. For instance, when the meteoric path is normal to the site-line AB of Figure 1, only coincidences with spacing s = 0 are possible. It is therefore necessary first to assume an equal distribution of radiants in that portion of the sky from which coincident meteors can be received, and then to compute the areas of sky which may contain radiants giving spacings between, say, s and (s + ds). The assumption that the radiants are uniformly distributed is probably met well enough if the observations are taken over a period of time, since the rotation of the Earth causes point radiants to appear as line radiants, and a group of line radiants placed across the active area of the sky at an arbitrary angle should be statistically uniform. It is then possible to compute the area of sky containing radiants capable of providing meteors with normal planes P_A and P_B (Fig. 1) having a separation between s and (s + ds). This area is $\pi ds/D$ steradians. A uniform distribution of radiants will therefore give a uniform distribution of plane spacings s.

The probable fraction of meteors detected at one station which will be detected at the other, $P_C(s)$, can then be expressed in terms of the reflection point spacing s as

$$P_C(s) = \int_s^\infty N(L)\,[1 - s/L]\,dL \Big/ \int_0^\infty N(L)\,dL \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

In order to solve this expression for the length distribution, differentiate twice, so that by calling the denominator of the right-hand member of (2) n, we have

$$N(s) = nsP_C''(s) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

In Figure 4 is shown the application of the formula of (3) to the data of Figure 3. Because of the roughness of the experimental ordinates, an accurate value of the second derivative can hardly be

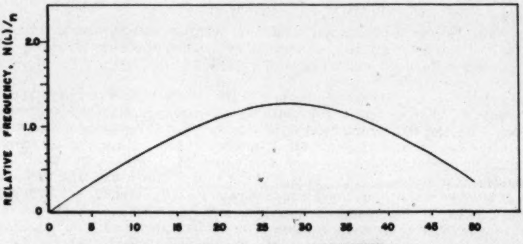

Fig. 4--The relative frequency of occurrence of trails of various lengths for sixth magnitude meteors; the breadth of the curve is not accurately defined by the scant data of Figure 3.

expected. The necessity of assuming a mean meteor velocity to convert from time difference to trail length has the effect of broadening the curve of Figure 3, and so will alter somewhat the peak of Figure 4. However, the magnitude of the most frequent trail length deduced from the experiment is probably quite representative for equipment of sensitivity comparable to that used in the test. Relatively low-powered transmitters were employed, and as a result the rate of detection of usable meteors was no more than 340 per hour. Quite possibly the trail lengths observed on more sensitive equipment would be somewhat shorter. Theory does not predict a rapid variation of trail length with meteoric magnitude, however, because of the exponential nature of the variation of atmospheric density with height.

If one assumes a trail length of 30 km, and assumes a maximum range of detection of 200 km, then considering only those meteors of the magnitude detectable by this equipment, calculation shows that only about 18 pct of the total number incident upon the atmosphere within 200 km of the observatory actually can be detected [MANNING, 1948]. The reason for the relatively small rate of detection is that these meteors can be detected only when their ionization trails are perpendicular to a ray from the observatory, and this is a very restrictive condition. Correcting the total rate by the factor of 1/0.18 calculated from the previous study [MANNING, 1948], we find a total rate of arrival of 2500 meteors per hour, with the mean trail length 30 km. It is to be expected, on the basis of the rate of arrival, that the smallest meteors involved in the present determination were of the sixth magnitude [WATSON, 1941]. The test was carried out at a time when there was a possibility of activity from the radiant of the Alpha Aurigids. However, no significant difference in the rate of meteoric arrival was noted in comparison with other, nonshower, nights. It is believed that very few shower meteors were detected during the tests.

Conclusions--By studying the rate of coincident detection of meteors at two widely separated locations as a function of the relative starting times of the echoes involved, it is possible to deduce the distribution in length of the meteoric ionization columns. A precise determination would require, in addition, that the velocity of the individual meteors used in the test be known, but in the absence of such data an approximate distribution of trail lengths can still be deduced, yielding a mean value that is probably representative of actual conditions. For equipment generating about one kilowatt of continuous-wave output, and capable of detecting meteors at a total rate of 450 meteors per hour, the mean trail length was found to be about 25 or 30 km. Calculations based upon this value of trail length, and upon the use of a corrected rate of meteoric arrival, show that meteors up to the sixth magnitude were detected during the test.

The method which has been described provides a measure of trail length dependent upon the ability of the trail to reflect a signal at normal incidence. The probable error of the determination of frequency of occurrence of trails of various lengths is independent of the rate of detection, but is inversely proportional to the square root of the period of observation.

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EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER AT AN AIR-EARTH INTERFACE

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Abstract--This paper is concerned with the instrumentation for, and the results from, an experimental investigation of heat transfer over a smooth dry-lake. The original data are on file in the Department of Engineering, University of California, Los Angeles. Heat-transfer rates into the ground were measured with thermopile heat meters; the net radiant exchange at the Earth's surface was measured with a net exchange radiometer. A continuous 48-hour record of these quantities, together with vertical convective heat-transfer rates determined from heat balances at the surface, is presented. Unit convective conductances (heat-transfer coefficients) are calculated from the convective transfer rates and differences between the surface temperature and the air temperature at a height of two meters. An empirical expression for the convective conductance, which agrees within ten per cent with the experimentally determined values, is presented.

A series of small thermocouples was used to measure the air-temperature distribution very close to the surface. Vertical convective heat-transfer rates calculated from these measured temperature gradients compare favorably with those from the heat balances. These measurements indicate the probable existence of a laminar sublayer, though further data are necessary for conclusive affirmation.

Introduction--Although numerous significant theoretical and experimental studies of turbulence in the lower atmosphere have been made during the past 30 years, many investigators are still studying it. These efforts are largely concerned with the problem of adequate instrumentation with which to evaluate theoretical developments as well as to inquire into the physical characteristics of turbulent transfer of heat, mass, and momentum. These physical characteristics are conveniently subdivided into (a) the structure of turbulence and (b) the macroscopic effects of turbulent flow. The latter is of special interest in this paper.

In the engineering sciences, a successful approach in heat-transfer studies with turbulent fluid flow has been based upon defining the convective heat-transfer rate as the product of a unit thermal convective conductance (heat-transfer coefficient) and a temperature difference, that is, potential difference. Because of the obvious physical similarity between a smooth natural surface and a horizontal flat plate in the laboratory, there is logical reason to suppose that convective heat-transfer rates in the former system would be influenced by some of the same parameters affecting convective transfer rates in the latter. Therefore, two important objectives of this investigation were to demonstrate further the value of several recently improved instruments for heat-transfer studies in the lower atmosphere and to indicate the usefulness of the concept of the unit thermal convective conductance in relating overall convective heat-transfer rates to pertinent variables.

Instrumental and observational aspects--Complex instrumentation requirements for basic diffusion studies in the lower atmosphere, with its large number of independent and uncontrollable variables, lead the investigator to seek a fundamental system which lends itself most readily to experimental analysis. To this end, the site of the dry-lake at El Mirage, California, offered many possibilities. The exceptionally level, hard-packed, dry-lake bed is about four miles long and varies in width up to one mile. It is oriented with the largest dimension in the northwest to southeast direction, which is also the direction of the prevailing wind. The unusual character of the surface, readily observed in Figure 1, reveals about 80 pct of the area to be very smooth while the remainder consists of irregular shallow channels or grooves approximately five millimeters deep. Because the surface condition shown in this picture is representative of that of the area within a radius of about 500 meters from the test site, this extensive surface is seen to be a satisfactory approximation to an infinite, smooth boundary. For many miles to the northwest and west the terrain beyond the lake area is level and covered with scattered brush about one meter high. To the north and east beyond the lake, however, a gentle slope, similarly covered with brush, rises to a low mountain range.

In the absence of simple instruments capable of a direct measure of the transfer of heat through a fluid medium in turbulent motion, it becomes necessary to resort to either heat-balance measurements or to temperature-gradient measurements in the laminar sublayer, if such a layer is present. Attempts were made to utilize both of these techniques in the present work.

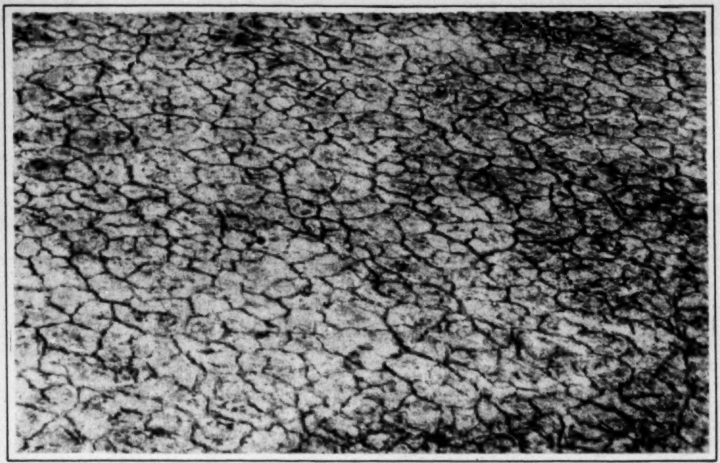

Fig. 1--A close-up of the dry-lake bed showing an area measuring approximately two by two meters

Heat-balance technique--A complete heat balance at the air-ground interface may be expressed as

$$(q/A)_{conv_o} + (q/A)_{e_o} = -(q/A)_{th_o} - (q/A)_{gr} - (q/A)_{g_o} \quad \ldots\ldots\ldots\ldots (1)$$

where $(q/A)_{conv_o}$ is convective heat-transfer rate per unit area at the ground, $(q/A)_{e_o}$ is heat-transfer rate per unit area due to evaporation or condensation of water vapor at the ground, $(q/A)_{th_o}$ is total hemispherical irradiation per unit area at the ground, $(q/A)_{gr}$ is total radiation emitted by and reflected from the soil surface per unit area (ground radiosity), and $(q/A)_{g_o}$ is heat transfer per unit area by conduction into or out of the Earth at the interface. A sign convention of plus and minus is observed for heat flow into and away from the boundary (air-ground interface), respectively. With this convention, it should be noted that $(q/A)_{th_o}$ is always positive and $(q/A)_{gr}$ is always negative.

If the heat transfer by evaporation is not small compared to convection, approximative procedures must be employed to separate these terms, presuming no direct measure of the natural rate of evaporation is available. Carefully preserved samples of soil from the upper half-inch layer were oven-dried and found to contain about two per cent moisture on a dry weight basis. Since the soil contained a high percentage of clay and silt, the moisture percentages given are reasonably representative of the amount that would be held loosely bound by the adsorptive forces of such a fine-textured soil mixture. Furthermore, soil samples taken at sunrise and in the early afternoon (that is, when the soil temperatures were at minimum and maximum values, respectively) substantiate the above statement by giving approximately the same moisture percentages. Thus, by showing that practically no moisture was available for evaporation, the latent heat-transfer rate must have been negligibly small. This is, of course, to be expected for the extremely arid dry-lake bed, and affords yet another reason for choosing such a site for experimental purposes.

A further simplification can also be made by noting that

$$(q/A)_n = (q/A)_{th_o} + (q/A)_{gr} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $(q/A)_n$ is net radiant-energy exchange per unit area of the interface. Thus, the vertical convective heat-transfer rate can be determined from the relation

$$(q/A)_{conv_o} = -(q/A)_n - (q/A)_{g_o} \quad \ldots\ldots\ldots (3)$$

Measurements of the net radiant-energy exchange and ground conduction terms have been greatly simplified by the development of a heat-flow meter at the University of California, Berkeley [MARTINELLI, 1942; BOELTER, 1944]. A typical heat meter consists of a silver-constantan thermopile of about 700 junctions with alternate junctions on opposite sides of a thin sheet of bakelite, the whole being sandwiched between two thin sheets of the same material. As the total thickness is only 1.2 mm, the resistance to heat flow through the meter is quite small. The calibrated voltage response of the thermopile is the measure of heat flow through this instrument. An iron-constantan thermocouple is made an integral part of the meter to allow for correction if the meter is used at a temperature other than that at which it was calibrated.

To measure heat flow into or out of the Earth by conduction, two heat meters were placed within a few feet of each other at depths of two mm and one mm below the surface. Installing the meter at two mm below the surface (henceforth designated as H.M. No. 1) consisted of making a shallow depression in the soil surface, seating the meter firmly against the bottom to eliminate any possible air gap, and then covering the meter with a thick paste of surface soil and water. Care was taken to reproduce the shallow grooves characteristic of the surrounding surface. The procedure for the meter placed one mm deep (henceforth designated as H.M. No. 2) differed only in the covering applied, which consisted of a thick paste of soil and water with 12 pct cement added as a binder. This paste was smoothed over the meter with no attempt to duplicate the natural surface. An interval of several days elapsed between the installation and the use of both heat meters.

The net exchange of radiant energy between the Earth and its surroundings was measured with a net exchange radiometer which employs a heat meter as the sensitive element. Since this instrument has been completely described by GIER and DUNKLE [1951], it is sufficient to note here that the heat meter is mounted in a high-velocity air stream for the purpose of maintaining equal convective heat-transfer rates on both sides of the sensing element. The calibration constant of the instrument has been experimentally demonstrated to be independent of the wave length of the incident radiation. This is readily seen to be a very desirable feature in view of the wide range in the spectral distribution of radiant energy in the atmospheric system.

Thus, for the conditions described, the vertical convective heat flow can be obtained from relatively simple measurements of the net exchange and ground conduction with these instruments. Other types of radiometers and heat meters, some of which are described in KLEINSCHMIDT [1935, pp. 177-185], have been employed by ALBRECHT [1940] and others to make similar measurements.

Temperature-gradient technique--Vertical convective heat-transfer rates can also be experimentally determined from the product of the temperature gradient in the laminar sublayer (provided such a layer is present) and the thermal conductivity of the fluid, that is,

$$(q/A)_{conv_o} = -k\,(\partial t/\partial z)_{z=0} \quad \ldots\ldots\ldots (4)$$

Conversely, if the vertical convective heat-transfer rate has been measured by some other technique, and good agreement with this value can be obtained by inserting in (4) a measured value of the temperature gradient near the surface, then the presence of a laminar sublayer has been demonstrated.

Temperature measurements at eight heights in the first few centimeters above the surface were made with fine butt-welded thermocouples constructed of 0.077-mm diameter chromel-alumel wire. Nominal heights of measurement were 25, 12.5, 6.2, 3.1, 1.5, 0.75, 0.5, and 0.25 mm above the surface. It was hoped the thermocouples closest to the surface would give the temperature gradient within the laminar sublayer.

The support for the thermocouples consisted of two tapered pieces of lucite supported by a small circular base (see Fig. 2) containing a mixture of soil from the dry-lake surface and a few per cent cement as binder. By placing the smooth upper surface of this base flush with the surrounding surface, the thermal and hydrodynamic systems remained essentially undisturbed. This

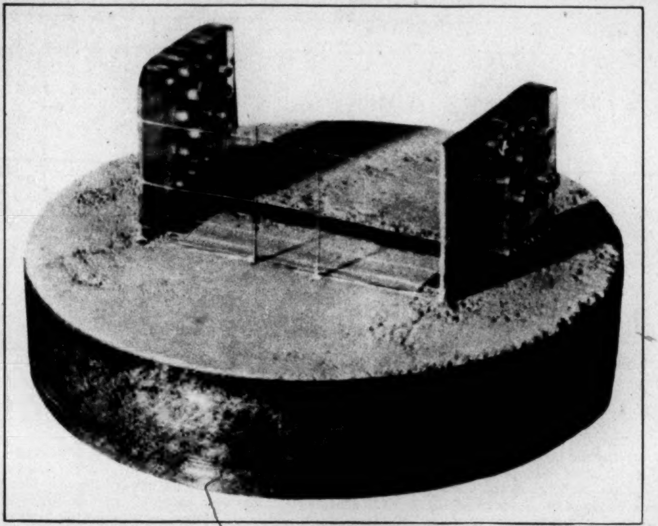

Fig. 2--Thermocouple rake used to measure air temperatures near the surface (actual diameter of base 11 cm)

was verified by actual measurements which showed that the surface temperature of the base differed from that of the surroundings during the mid-day hours by less than 0.5° C. At frequent intervals during the test runs, because of thermal expansions of the supports, measurements of the heights of the four lowest thermocouples above the surface were made with the aid of an optical system and scale.

Because of spatial limitations there was no temperature sensitive element at the convenient reference height of two meters. Thus, it was necessary to interpolate the air temperature at this level from the vertical temperature distribution, which was measured by means of eight shielded thermocouples placed at various positions on a mast 15 meters in height. Wind velocities were measured at several heights with sensitive, three-cup anemometers; one height being the two-meter reference level.

Results and discussion

Time variation of heat-balance components--Values of the net radiant-energy exchange at the interface and of the heat transfer into or out of the Earth by conduction as determined from recorded measurements with the instruments previously described are shown (Fig. 3), as well as the vertical convective heat-transfer rate calculated from (3). Where few or no actual data are present to permit this calculation, it is then based on interpolations of the data, with a maximum expected error of less than 15 pct in the magnitude of the convection rate so determined. Because of the relatively constant synoptic conditions during this interval, it is not surprising that heat-transfer rates are very similar for the two 24-hour periods shown in this figure.

Since the heat meters used to measure the ground conduction are of finite thickness and were placed at different depths below the surface, it was necessary to correct for the heat stored in the volume of soil and bakelite between the thermopile and surface. The sum of these corrections did not exceed 0.014 gm cal/cm^2 min. In this paper, calculations involving use of the ground conduction heat-transfer rate are based on the average curve drawn through the data, which have been corrected for the storage term.

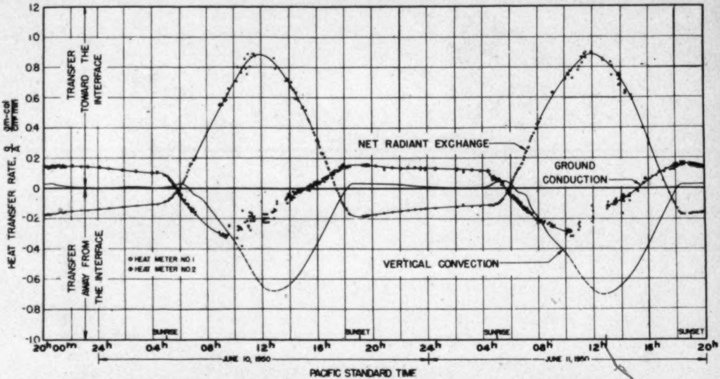

Fig. 3--Net radiant exchange at the interface, ground heat conduction, and vertical convective heat-transfer rates as a function of time at El Mirage dry-lake, California

During the hours from 23h 00m on June 9 to 04h 00m on June 10 and from 00h 00m to 04h 00m on June 11, it is observed that the convective heat-transfer rate was essentially zero; that is, the net radiant exchange at the surface was balanced by the transfer of heat toward the interface by ground conduction. Supplementary records show that during these hours of greatest atmospheric stability, air speeds were very low (less than one m/sec) and differences between the surface temperature and the air temperature at a height of two meters were quite small (less than 2° C). Under these conditions, heat-transfer theory shows there can be but little convective transfer. For the limiting case of an adiabatic temperature distribution in the layer of air adjacent to the Earth, the convective transfer must be zero. Thus, the agreement with theory provides an important check on the reliability of the heat meter-radiometer combination.

It is also of interest to examine in somewhat greater detail the net exchange of radiant energy at the Earth's surface by expressing (2) in the form

$$(q/A)_n = \alpha_s \, (q/A)_{th_o} + \epsilon_s \, \sigma \, T_s^4 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where α_s is absorptivity of the Earth's surface, ϵ_s is emissivity of the Earth's surface, σ is Stefan-Boltzmann constant, and T_s is mean air-ground interface temperature (absolute). Using measurements of the spectral reflectivity of soil samples from the dry-lake bed, it was determined that for long-wave-length radiation the average surface emissivity (equal to the average absorptivity) was 0.9. Mean interface temperatures were calculated from temperatures given by the thermocouple embedded in Heat Meter No. 1. This latter calculation, based on the Fourier conduction equation, was made using measured values of the thermal conductivity of the soil and assuming a linear vertical temperature gradient in the upper two mm layer of soil. From this information and measured values of the net radiant exchange, the total hemispherical radiation for long-wave-length sky (nocturnal) radiation for the period 20h 00m, June 10, to 05h 00m, June 11, was determined from (5). Direct measurements of the nocturnal radiation from half space were also made with a total hemispherical radiometer [GIER and DUNKLE, 1951], which is nonselective with regard to wave length of the incident radiation. Comparison of the measured and calculated values is made in Figure 4. The excellent agreement is a further and very desirable indication of the reliability of the instruments and indirectly supports the validity of the various experimental techniques.

Direct measurement of vertical convective heat-transfer rates--Numerous investigations of turbulent flow in tubes and flat ducts have shown that velocity fluctuations decrease quite rapidly in magnitude as the boundary is approached [LAUFER, 1950]. Fewer data are available for the case of temperature fluctuations in non-isothermal systems, but there is little reason to suppose a similar diminution would not occur. The presence of a laminar sublayer in turbulent flow with heat transfer could, therefore, be proved by demonstrating the absence of either temperature or velocity fluctuations near the surface. Although examination of original records did show a sudden decrease in temperature fluctuations below a height of 1.3 mm, the fluctuations of all temperatures obtained showed that the thermocouples were above the laminar sublayer.

Nevertheless, it is still of interest to calculate the vertical convective heat-transfer rate from Fourier's conduction equation, (4). Temperature gradients at a height of 0.43 mm (the location of the next to lowest thermocouple) were taken from smooth curves drawn through the data. Convective heat flows calculated from (4) using these gradients are compared in Figure 5 with convective heat flows determined from the heat balances. Agreement within a factor of two is very encouraging. Since the temperature gradient below a height of 0.43 mm was still increasing as the surface was approached, it is strongly believed that had it been possible to place one or more thermocouples below a height of 0.25 mm, the convective transfer could have been determined by this technique with good agreement. Thus, the presence of a laminar sublayer, which can now only be inferred, would have been demonstrated with little doubt.

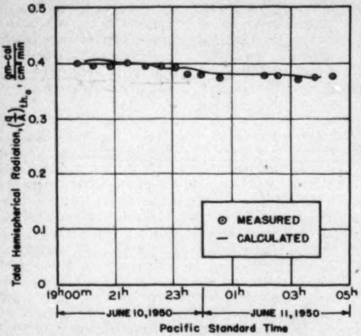

Fig. 4--Comparison of the long-wave-length radiation on the Earth's surface as determined by a total hemispherical radiometer and by a radiation balance

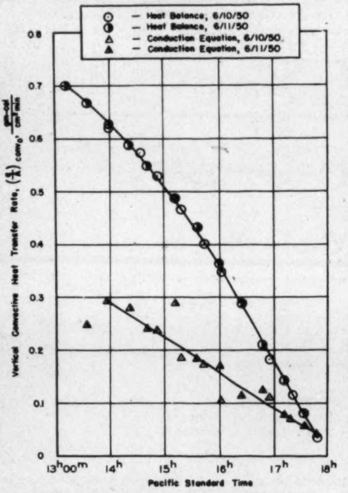

Fig. 5--A comparison of convective heat-transfer rates as determined from a heat balance and by the conduction equation

Correlation of convective heat-transfer data--One of the approximate expressions used in studies of turbulent diffusion relates the rate of transfer of the diffusing quantity to an eddy diffusivity and a potential gradient [BRUNT, 1939]. Many studies conducted to determine the precise values of the eddy diffusivity and its relation to other physical parameters of the system, have revealed limitations of this concept. In an attempt to overcome some of these difficulties, other studies have made an appeal to the concept of relating convective heat-transfer rates to a unit thermal convective conductance (heat-transfer coefficient) and a temperature difference. McADAMS [1942] gives

$$(q/A)_{conv_0} = f_c\,(t_s - t_f) \ldots\ldots \quad (6)$$

where f_c is unit thermal convective conductance (heat-transfer coefficient), t_s is surface temperature, and t_f is fluid temperature far from the surface. Application to systems of finite dimensions has been quite successful because of extensive experimentally determined relations between the convective conductance and parameters of the system. These relations, unlike those for the eddy diffusivity, have shown good agreement over wide ranges in the magnitudes of the physical parameters.

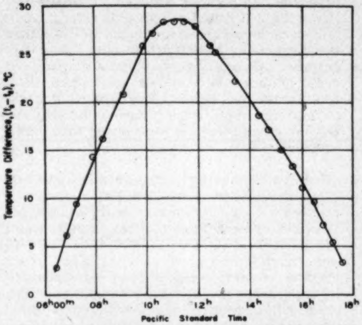

Fig. 6--Temperature difference between the surface and the air at a height of two meters as a function of time for June 11, 1950

For the present application, t_f was replaced by t_2, the air temperature at a height of two meters; surface temperatures were determined in the manner previously described. A typical daytime variation of the temperature potential, $(t_s - t_2)$, is shown in Figure 6.

Time variation of the convective conductance for June 11, calculated from (6), is presented in Figure 7. Wind-velocity variation at a height of two meters for the same day is also plotted on this graph to demonstrate the relationship between these quantities. Similar trends were noted for the data taken on June 10. In the above calculations and comparisons, measurements of heat transfer, temperature, and velocity were selected only for those periods when conditions were reasonably steady. The selections were necessary because of the limitations imposed by the various instruments themselves in that there is obvious difficulty in obtaining reliable average values during periods of extreme variability. Also, data for periods of not less than seven minutes were analyzed; the average length was about 15 minutes. During the night and transition periods the magnitudes of convective heat transfer and the temperature differences were so small that the probable percentage errors were too large to permit the use of measurements taken during these periods.

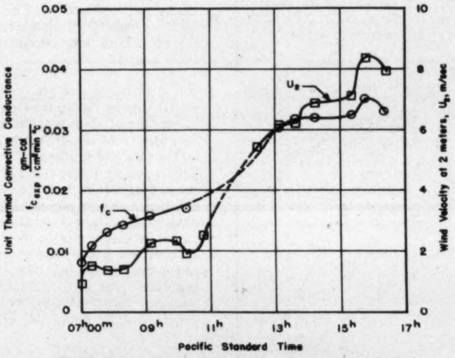

Fig. 7--Unit thermal convective conductance and wind velocity at two meters as a function of time for June 11, 1950

At this point it is convenient to note that extensive investigations of convective heat transfer from finite, horizontal, smooth, flat plates in air have produced the following results [TRIBUS and MORRIN, 1950]

(a) Forced convection $$f_{c_1} = b_1 T_M^{0.3} (U_\infty \gamma)^{0.8}/D^{0.2} \quad . . . . (7)$$

where b_1 is an experimentally evaluated constant, T_M is average absolute temperature of the layer extending from the surface to a height far from the surface, U_∞ is air velocity far from the surface, γ is air density, and D is length of the plate, and

(b) Free convection (buoyancy effect) $$f_{c_2} = b_2 \left[(t_s - t_f)/D\right]^{0.25} \qquad (8)$$

where b_2 is an experimentally evaluated constant. For a large plate it is evident that f_{c_1} and f_{c_2} are relatively insensitive to small changes in D. Further, it is obvious that for $D = \infty$, both of these expressions reduce to zero. Therefore, in a system without significant dimensions it is proposed to modify these relationships and combine them empirically to obtain

$$f_{c_{emp}} = f_{c_1} + f_{c_2} = B_1 T_m^m U_2^n + B_2 (t_s - t_2)^p \qquad (9)$$

where B_1, B_2 are constants to be experimentally determined, m, n, p are exponents to be experimentally determined, T_m is $273 + (t_s + t_2)/2$, U_2 is air velocity at a reference height of two meters, and t_2 is air temperature at the same reference height. Since the actual turbulence mechanism under unstable conditions undoubtedly cannot be adequately represented by the above superposition of approximate solutions, the justification for this procedure rests on its simplicity and the fact that only a limited quantity of data was available with which to establish the constants in this empirical expression.

Trial and error procedures of determining these constants and exponents from the experimental convective conductance data yielded

$$f_{c_{emp}} = 0.000144\, T_m^{0.3} U_2^{0.7} + 0.00097\, (t_s - t_2)^{0.3} \qquad (10)$$

as the best combination. In Figure 8, comparison of values calculated from this expression with the experimental conductance data shows agreement within ten per cent. It should also be noted here that wind velocities at the two-meter height varied from 0.8 to 8.5 m/sec and the temperature difference varied from 6.7 to 27° C. These ranges denote at least a fair degree of generality for the empirical expression in so far as this specific system is concerned. As more data become available, this empirical equation naturally will be modified and the effects of other parameters taken into account by addition of other factors.

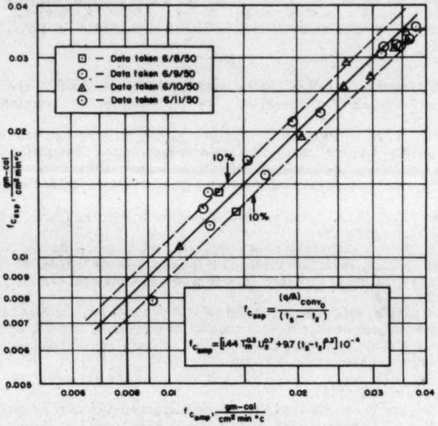

Fig. 8--A comparison of $f_{c_{emp}}$ with $f_{c_{exp}}$

The importance of buoyant forces in the eddy transfer of heat has been recognized by numerous investigators. Although theoretical treatments by PRIESTLY and SWINBANK [1947] and SUTTON [1948], along with additional experimental verification by PASQUILL [1949], have represented significant contributions, much work remains to be done on this problem. Therefore, the present analysis has been, in part, an attempt to separate total convective heat-transfer rates into components of forced and free convection. Assuming (10) to be reasonably valid, the results show that during the mid-morning hours when wind velocities were low (about 1 to 2 m/sec), the transfer by free convection may have been about 20 pct of the transfer by forced convection. Thus, supporting previous theoretical and experimental investigations, there is indication that free convection is a significant part of the overall convective heat-transfer rate under such conditions.

Because all of the data presented in Figure 8 were obtained during unstable conditions (that is, when the surface temperature was greater than the air temperature), no valid predictions can be formulated regarding the behavior of the convective conductance in a stable atmosphere. Therefore, it is hoped that further experimental studies will include not only the effects of stability, but also those of ground roughness. Once these effects have been determined, it is believed that the use of the unit thermal convective conductance will become more firmly established, thus greatly simplifying the problem of determining overall convective heat-transfer rates in the lower atmosphere.

Conclusions

As a result of this investigation, the following conclusions may be noted: (1) Vertical convective heat-transfer rates (in the absence of evaporation or condensation) can be determined in a wholly reliable manner from measurements with two relatively simple instruments, that is, with the net exchange radiometer and the heat meter. (2) Air temperature measurements very close to the Earth's surface indicate the existence of a laminar sublayer. Vertical convective heat-transfer rates calculated from the Fourier conduction equation agreed with the values determined as in (1) above within a factor of two. More conclusive evidence must await refinement of present techniques. (3) Taking into consideration the effects of free and forced convection in the transfer of heat from a smooth, flat boundary, experimental convective conductances have been expressed empirically within ten per cent.

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CUBE-ROOT-NORMAL PRECIPITATION DISTRIBUTIONS

C. K. Stidd

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Abstract--It is observed that the cube roots of precipitation amounts often are distributed normally. This is found to apply to data for stations ranging from arctic to tropic regions, from extremely wet to extremely dry regions, and for precipitation periods of one day to one year. For comparison, sets of data that have been analyzed by other methods are examined. Certain exceptions to and limitations on the generality of the normal distribution of the cube roots of precipitation amounts are pointed out. Ways of using this characteristic are discussed.

Introduction--The normal distribution curve is of recognized value as a first approximation to many distributions observed in nature, despite the fact that in most applications it cannot be proved to apply with rigor. For this reason, and due to the fact that the normal curve is easy to work with mathematically, a large number of useful statistical techniques and tables have been developed for the testing of data that are assumed to be normally distributed. Probability estimates, correlations between variables, statistical forecasting, and quantitative descriptions of climatic variability furnish examples of problems that are much easier to handle if the basic data are normally distributed or can be "normalized."

Many pressure and temperature data have distributions for which the normal assumption may be made without serious error. Precipitation, however, needs special treatment, and the material that follows will illustrate a simple method by which most single-station precipitation records can be "normalized."

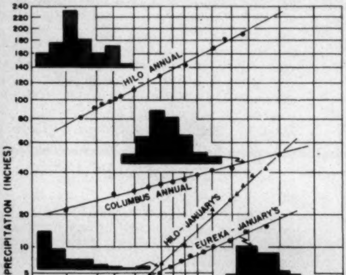

Fig. 1--Distribution of monthly and annual precipitation amounts on a cube-root probability graph; data pictured are annual for Hilo, Hawaii, and Columbus, Ohio, and January for Hilo, Eureka, and Pueblo; inserts are equal interval histograms of the same data

Graphical representation--The precipitation distributions shown in the figures are ogives, or cumulative frequency diagrams, which have been linearized by the use of special scales. With a linear vertical scale and a probability abscissa [HAZEN, 1930] a normal distribution plots as a straight line. It has been found, largely through trial and error, that precipitation data often will plot as a straight line on a diagram with a cube-root vertical scale and a probability abscissa. This characteristic, indicating that the cube roots of precipitation amounts are normally distributed, seems to apply to the great majority of single-station records from all parts of the world and for daily, monthly, and annual amounts.

Some typical precipitation distributions are pictured in Figure 1. The inserts are histograms which illustrate the varying degree of "skewness" or asymmetry to be found in precipitation data. The straight line (fitted by eye to the plotted points) associated with each histogram is the ogive, or integral, of the histogram. The skewness is, in general, greater for dry stations than for wet, and greater for data with large variability than for data with small variability, but for all the data pictured here the skewness is effectively removed by use of the cube-root transformation. The straight line suggests that precipitation distributions can be described adequately by two parameters, for example, the median (level at which the line crosses the 50 pct ordinate), and the slope (proportional to the standard deviation of cube roots). The straight line also indicates that, if a given record contains no zeros, the cube roots of its values may be treated by statistical methods that are based on the normal assumption. The effect of zeros in the data will be discussed subsequently.

Physical causes--The use of a "normalizing function" [EDGEWORTH, 1898; KAPTEYN, 1903; KAPTEYN and VAN UVEN, 1916] for the description of a distribution has the advantage of giving some hint as to the physical causes of the distribution. In this case, the applicability of the cube root suggests that precipitation is a function of the cube of some normally distributed parameter or, more generally, the function of the product of three normally-distributed and intercorrelated parameters. These might be the vertical motion, moisture content, and duration time (frequency). This consideration is highly speculative, however, and is intended only as a thought-provoking sidelight.

No very satisfactory answer can be given to the question as to why the cube root should be used in preference to the square root or fourth or higher root, and, in fact, there is no reason why some other root should not be used in special cases where it may be found to be suitable. In the event that the cube root does not remove enough of the skewness (as evidenced by a systematic convex-downward curvature of the plotted points), a higher root may make the array of points more nearly linear.

The cube-root transformation is in effect a "skewness-removing mechanism" and, in practice, it seems to remove just that amount of skewness that is to be found in most precipitation data from individual stations. By this token it should not necessarily be expected to apply to rainfall amounts that have been averaged over an area since the averaging process, itself, may remove some of the skewness, and the cube root might be expected to over-correct such data. Some attempts to analyze areal averages by the cube-root or other simple transformations have yielded unsatisfactory results For a more general method, which may apply to the problem of areal precipitation distribution, the reader is referred to the paper of BARGER and THOM [1949].

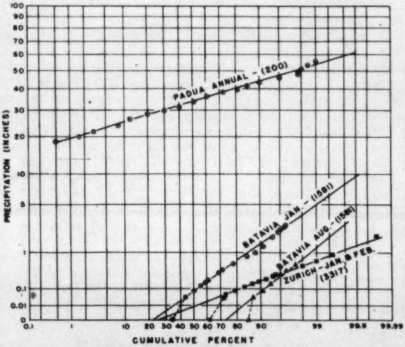

Fig. 2--Distribution of annual precipitation amounts for Padua, Italy, and daily amounts in January for Batavia, and in January and February for Zurich; figures in parentheses are the years (Padua) or days (Batavia and Zurich) of record; data from CONRAD and POLLAK [1950]

Test of the method on published distributions--In Figure 2 the Padua annual amounts [CONRAD and POLLAK, 1950] are an example of data that are nearly normally distributed. The data also fit the cube-root-normal graph very well as do the daily amounts at Batavia and Zurich. In these daily amounts, however, the zero points fall at higher percentages than would be indicated by extrapolation of straight lines. This tendency has been found in all data containing zeros, unless traces as well as zeros were recorded. In data that record traces, the recorded percentage of zeros is a true one, and it falls in line with the other points. Since traces are usually recorded as zero, the percentage of zeros will be artificially inflated in most records. If a trace may be defined as any amount between zero and 0.01 inch, the graphs show that a substantial percentage of them may be expected to occur. For instance, from the straight line representing the Zurich data it might be inferred that 27 pct (52 pct at 0.01 minus 25 pct at zero) of all days should have had a trace of precipitation. It is due to the zeros in precipitation data that graphical rather than arithmetical methods of data treatment have been used. The standard deviations of the cube roots of precipitation amounts are proportional to the slopes of the lines for those sets of data which contain no zeros. This cannot be true for such arrays as those for Zurich or Batavia since the straight lines are discontinuous at zero. BARGER and THOM [1949] overcome this difficulty by considering separately the situation of no precipitation and the distribution of actual precipitation amounts. On a cube-root-normal graph, however, the distribution line will not be straight unless the zeros are included. This suggests that the causal factors of precipitation have a distribution that is continuous, the positive portion being associated with the actual amounts of precipitation and the negative portion being associated with the zeros.

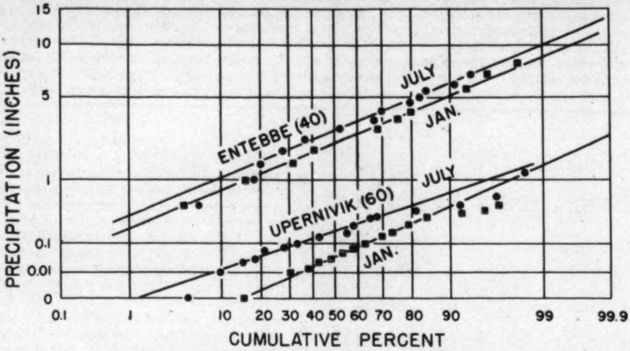

Fig. 3--Distribution of January and July precipitation amounts for Entebbe and Upernivik; the figures in parentheses are the months of record

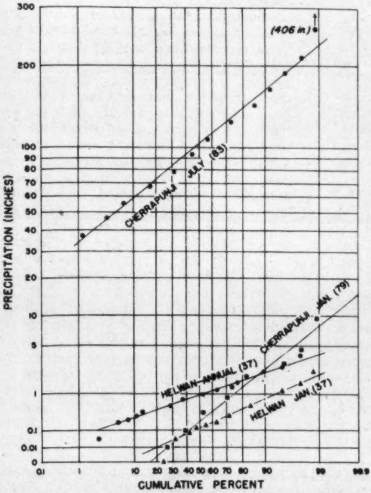

Fig. 4--Distribution of January and July precipitation amounts for Cherrapunji, India, and January and annual amounts for Helwan, Egypt (all July values at Helwan are zero); figures in parentheses are the months (Januaries in Helwan and Cherrapunji) or years (Helwan, annual) of record

Other tests of the method--The method has been tested on several of the most extreme precipitation climates that can readily be found. In Figure 3 are shown January and July distributions for Entebbe, Uganda (0° 5′ N lat.), and for Upernivik, Greenland (72° 47′ N lat.). Of the long-record stations listed in World Weather Records [CLAYTON, 1917, 1944, 1947] these are the two which lie closest to the equator and to the pole. The flattening-out of the upper ends of the Upernivik arrays is likely to be accidental; none of the other ten months displays this tendency. Figure 4 shows tests of the method on the wettest and driest climates for which monthly records are available. The highest July value for Cherrapunji, if plotted in its proper position, would fall well beyond the end of the vertical scale, but the rest of the points may be fitted by a straight line.

Exceptional cases--Among 40 or 50 additional distributions plotted, the only ones that could not be fitted satisfactorily by straight lines were those from small ocean islands, Malden Island, near the equator, and Laurie Island, at high southerly latitudes. The Hawaiian Islands yielded some data that were well fitted by the cube-root-normal distribution and some that were not. The method may apply rather generally to continental data but it should be used cautiously in regions under predominantly maritime influence.

Practical applications--The method, so far, has been used to normalize precipitation data so that meaningful correlation coefficients between precipitation amounts and other climatic factors may be computed. Where comparisons have been made, the coefficients for normalized data have been higher than those for untreated data. In any event, the skewness must be removed if significance tests are to be used with any great degree of confidence. In another application, the method has been used to estimate class-limits for ten-day precipitation amounts from a knowledge of five- and 30-day class-limits. The estimates were admittedly rough, but they could be made quickly and were more realistic than estimates based on simple straight-line interpolation. The method has also been used to smooth order-of-magnitude arrays of precipitation data for purposes of interpolation.

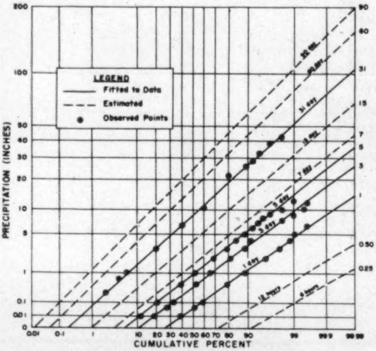

Fig. 5--Distribution of precipitation for various period lengths for Hilo, Hawaii, in January; the one-, three-, and five-day-period data are each based on 1300 cases and the 31-day-period data are based on 42 cases; the dashed lines are estimated; the spacing of the intersections of the family of lines with the 99.99 pct ordinate follows Fletcher's rule

In Figure 5 a family of the graphs is used to give a complete description of the rainfall climate for a single station (Hilo, Hawaii) during a given season (January), The circled points on the graph are the observed values for one-, three-, five-, and 31-day amounts and are fitted by solid lines. The dashed lines are estimated for other period lengths. The spacing of the lines seems to follow the rule [FLETCHER, 1950] for the envelope of world record-point rainfalls. The formula is $R = K D^n$, where R is the record rainfall amount, D is the duration time, and K and n are arbitrary constants to be determined empirically. In the present application, the value at which a line crosses the 99.99 pct ordinate is considered the equivalent of a "record rainfall amount" and is used as R in the formula. Thus two lines give two pairs of values for R and D and allow the constants K and n to be determined. This establishes the spacing for the entire family. In theory, the lines should be parallel since the crossing of any two lines would lead to the absurd implication that, beyond the point of intersection, the expected amount for a short period would be greater than the expected amount for a longer period. In practice, however, as in the case for the Hilo January data, a small degree of convergence will often be found. This helps illustrate the danger of extrapolating the individual lines beyond the area of observed data for the purpose of estimating the liklihood of flood or drought. Extrapolation of period length is also unjustified where accuracy is critical, and the two upper and two lower lines in the family of Figure 5 were included only to illustrate the method's possible use for making rough estimates.

Conclusions--The assumption of a normal distribution of the cube roots of precipitation amounts offers a simple method of making quantitative descriptions and comparisons of precipitation climates. Errors in the assumption will not be serious when it is used as a mechanism for interpolation or smoothing, but there is little present justification for extrapolating far beyond the limits of observed data. The assumption applies to single-station data and not, in general, to areal averages. The assumption fails to apply in a satisfactory manner to data from some small ocean islands and it is entirely possible that other exceptions exist. For the assumption to apply to data containing zeros, the zeros must be considered as representative of negative amounts.

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THE EFFECT OF A BROKEN ICEFIELD ON WATER WAVES

A. Shapiro and L. S. Simpson

Abstract--Methods of forecasting sea and swell in the open ocean have been given by Sverdrup and Munk and others. In this paper are presented principles from which techniques for forecasting sea and swell in a broken icefield may be developed. It is shown that water waves entering an icefield are damped exponentially with increasing ice thicknesses. It is further shown that selective damping occurs in the icefield, the shorter-period waves being more easily damped. Graphs are included which help to give a clearer picture of the results.

Introduction--Although the problem of forecasting deep water wind waves has been discussed [SVERDRUP and MUNK, 1947], very little work of a practical nature has been done to determine the effect of a broken icefield on deep water waves. However, two recent papers [PETERS, 1950, and WEITZ and KELLER, 1950] present a comprehensive mathematical treatment of this problem. It is the purpose of this paper to utilize some of these theoretical results to derive practical formulas for obtaining the modification of sea and swell in and out of an icefield due to the effect of ice. This problem naturally divides itself into three parts.

(a) Given the period, amplitude, and angle of incidence of a wave approaching an icefield, the amplitude, wave length, and angles of refraction and reflection of the wave entering and leaving the icefield, respectively, are determined.

(b) Given the period, amplitude, and angle of incidence of a wave in an icefield approaching its outer edge, one can compute the amplitude, wave length, and angle of refraction of the wave leaving the icefield, and the angle of reflection of the wave back into the icefield.

(c) In part (a) an inconsistency exists in that the amount of wave energy approaching the icefield is not compatible with the sum of the wave energies reflected back from and transmitted into the icefield. This inconsistency occurs through an application of the theory of WEITZ and KELLER [1950]. In like manner the identical inconsistency appears when one considers part (b). It is proposed to eliminate these inconsistencies by the introduction of a new factor, which may be called ''pressure energy.''

Assumptions and terminology--The mathematical theory of the problem is simplified by the following assumptions. (1) The wave form is sinusoidal. (2) Frictional losses are negligible. (3) A steady-state condition with respect to wave height exists everywhere ($d\eta/dt = 0$). (4) The period (T) is the same in and out of the icefield. (5) The motion of the water is irrotational (no vortices) and solenoidal (property of an incompressible fluid). This yields the LaPlace equation for the velocity potential. (6) The displacements and velocity of the particles of the wave motion are small so that terms of the second or higher order can be neglected in the Bernoulli and continuity equations (linearized wave theory). (7) The boundary between the open water and the icefield is considered to be linear.

These assumptions are necessary in order to obtain a solution of the differential equation involved.

Figure 1 shows the icefield and the surrounding waters involved in the problem. The terminology is as follows.

Ew_0	Energy per unit width of incident wave approaching icefield
ηw_0	Amplitude of incident wave approaching icefield
λw_0	Wave length of incident wave approaching icefield
θw_0	Angle of incidence of waves approaching icefield
ER_1	Part of Ew_0 reflected from icefield
ηR_1	Amplitude of waves reflected from icefield
λR_1	Wave length of waves reflected from icefield
θR_1	Angle of reflection of waves reflected from icefield
ET_1	Part of Ew_0 transmitted into icefield
Ew_1	Part of ET_1 that goes into wave energy
Ew_1	Incident wave energy in icefield

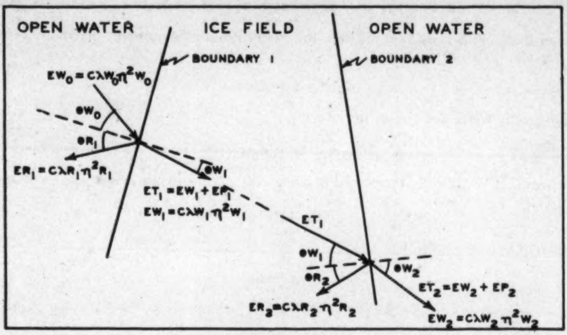

Fig. 1--Elements of the problem

ηw_1	Amplitude of transmitted wave in icefield
ηw_1	Amplitude of incident wave in icefield
λw_1	Wave length of transmitted wave in icefield
θw_1	Angle of refraction of transmitted wave in icefield
EP_1	Part of ET_1 that is transformed into pressure energy
$\theta' w_1$	Angle of incident wave in icefield
ER_2	Energy per unit width of reflected wave in icefield
ηR_2	Amplitude of reflected wave in icefield
λR_2	Wave length of reflected wave in icefield
θR_2	Angle of reflection of reflected wave in icefield = $\theta' w_1$
ET_2	Part of Ew_1 transmitted out of icefield
Ew_2	Energy per unit width of waves transmitted from icefield
λw_2	Wave length of transmitted wave out of icefield
ηw_2	Amplitude of transmitted wave out of icefield
EP_2	Part of Ew_2 which came from pressure energy
θw_2	Angle of refraction of transmitted wave from icefield
c	$\rho g/2$
ρ	Density of water
g	Acceleration of gravity

Formulation and solution, Problem (a)--WEITZ and KELLER [1950] define the reflection coefficient, which is the ratio of the amplitude of the reflected and incident waves, as $-N_+(\sigma)/N_+(-\sigma)$.

Now, employing Weitz and Keller's expressions for $N_+(\sigma)$ and $N_+(-\sigma)$, we may write in their notation

$$N_+(\sigma)/N_+(-\sigma) = -K_+(\sigma)\,[\sigma - (r_0^2 a^{-2} - K^2)^{1/2}]/K_+(-\sigma)\,[-\sigma - (r_0^2 a^{-2} - K^2)^{1/2}] \ldots (1)$$

where

$$\sigma = (\rho_0^2 a^{-2} - K^2)^{1/2} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Now

$$K_+(\sigma) = L_+(\sigma)/M_+(\sigma) = \alpha \mathop{\pi}_{n=1}^{\infty} [(1 + a^2 K^2 r_n^{-2})^{1/2} - ia\sigma r_n^{-1}]/$$
$$\beta \mathop{\pi}_{n=1}^{\infty} [(1 + a^2 K^2 \rho_n^{-2})^{1/2} - ia\sigma \rho_n^{-1}] \ldots\ldots\ldots\ldots (3)$$

Introducing a like expression for $K_+(-\sigma)$ we have

$$K_+(\sigma)/K_+(-\sigma) = L_+(\sigma)\, M_+(-\sigma)/L_+(-\sigma)\, M_+(\sigma) \tag{4}$$

It can be seen that, in the above expression, the numerator is the complex conjugate of the denominator for all n, and as such

$$K_+(\sigma)/K_+(-\sigma) = 1 \tag{5}$$

ρ_o (2) is defined by Weitz and Keller in

$$\rho_o\, a^{-1} \tanh \rho_o = \beta \tag{6}$$

In this expression β is fixed by the period of the wave. As the depth $a \rightarrow \infty$, $\rho_o \rightarrow \infty$ and therefore

$$\rho_o/a \rightarrow \beta \tag{6a}$$

In like manner it can be shown that

$$r_o/a \rightarrow \alpha \tag{6b}$$

Using the expressions for α and β and (1), (2), and (5), we arrive at the following expression for the ratio of reflected to incident amplitudes

$$\eta R_1/\eta w_o = (\alpha^2 - K^2)^{1/2} - (\beta^2 - K^2)^{1/2}/(\alpha^2 - K^2)^{1/2} + (\beta^2 - K^2)^{1/2} \tag{7}$$

at boundary 1, where $\beta = w^2/g$, $K = (2\pi \sin \theta w_o)/\lambda w_o$, $w = 2\pi/T$, and T = period of wave.

Now, if we write the following expression for α [WEITZ and KELLER, 1950]

$$\alpha = \rho w^2/(\rho g - m w^2) \tag{8}$$

where m is defined as the surface density, and if we assume that $m = \rho\epsilon$ where ϵ is the thickness of the ice, then

$$\alpha = w^2/(g - \epsilon w^2) \tag{9}$$

Having arrived at an expression for the amplitude of the reflected wave, we now attempt to determine the amplitude of the wave transmitted into the icefield. It has been shown above that the portion of the incident energy that is reflected must be $\eta R_1^2/\eta w_o^2$ since the energy is proportional to the squares of the amplitudes [LAMB, 1945]. Ordinarily it could be concluded from this that the wave energy transmitted would be $1 - \eta R_1^2/\eta w_o^2$. In order to arrive at an expression for the amplitude of the transmitted wave it is necessary to consider the effect of changing wave length. To do this we may write

$$1 - \eta R_1^2/\eta w_o^2 = ET_1/Ew_o = \eta w_1^2\, \lambda w_1/\eta w_o^2\, \lambda w_o \tag{10}$$

Now the amplitude of the transmitted wave would therefore be

$$\eta w_1/\eta w_o = \sqrt{\lambda w_o/\lambda w_1}\, \sqrt{1 - \eta R_1^2/\eta w_o^2} \tag{11}$$

However, PETERS [1950] has shown that the amplitude of the transmitted wave is damped exponentially with increasing ice thickness. We assume, therefore, that the ratio of the transmitted wave amplitude to incident wave amplitude has the form

$$\eta w_1/\eta w_o = \sqrt{\lambda w_o/\lambda w_1}\, \sqrt{1 - \eta R_1^2/\eta w_o^2}\, e^{-\alpha\epsilon} \tag{12}$$

It is realized that an error might be inherent in this assumption. However, since the purpose of this paper is to derive useful and practical relationships, this error will not affect seriously the results as shown by the graphs.

Now $\eta w_o \sim \sin \beta x$, and $\eta w_1 \sim \sin \alpha x$. By definition of wave length

$$\beta(x + \lambda w_o) = \beta x + 2\pi \qquad \alpha(x + \lambda w_1) = \alpha x + 2\pi$$

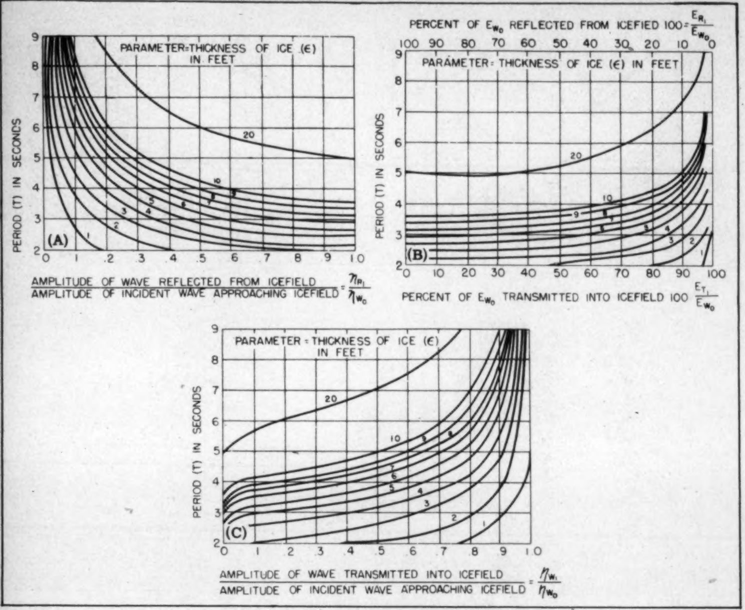

Fig. 2--Incident angle approaching icefield, $\theta w_0 = 0°$
($\theta w_1 = 0$ for all T and ϵ)

$$\therefore \lambda w_0 = 2\pi/\beta \qquad \lambda w_1 = 2\pi/\alpha \; \ldots\ldots\ldots\ldots\ldots\ldots \; (13a,b)$$

Expanding (12), we arrive at

$$\eta w_1/\eta w_0 = 2\sqrt{\alpha/\beta}\,(\alpha^2 - K^2)^{1/4}(\beta^2 - K^2)^{1/4}\,e^{-\alpha\epsilon}/[(\alpha^2 - K^2)^{1/2} + (\beta^2 - K^2)^{1/2}] \;..(14)$$

Those portions of Figures 2-4 which involve the reflected and the transmitted wave amplitudes and wave energy were computed from (7) and (14). The results are discussed later.

Problem (b)--It is now necessary to consider a wave in an icefield, and to arrive at relationships involving the wave energy and amplitude of a wave transmitted from and reflected back into the icefield. This may be done using the same method as for Problem (a). The resulting relationships are

$$\eta R_2/\eta w_1 = (\alpha'^2 - K'^2)^{1/2} - (\beta'^2 - K'^2)^{1/2}/[(\alpha'^2 - K'^2)^{1/2} + (\beta'^2 - K'^2)^{1/2} \;\ldots\; (15)$$

$$\eta w_2/\eta w_1 = 2\sqrt{\alpha'/\beta'}\,(\alpha'^2 - K'^2)^{1/4}(\beta'^2 - K'^2)^{1/4}\,e^{\beta'\epsilon}/[(\alpha'^2 - K'^2)^{1/2} + (\beta'^2 - K'^2)^{1/2}] \;. (16)$$

where

$$\alpha' = 2\pi/\lambda w_2 \qquad \beta' = 2\pi/\lambda w_1 \qquad K' = 2\pi \sin\theta w_1/\lambda w_1 \;\ldots\ldots\; (17a,b,c)$$

Equations (15) and (16) were used to compute that part of Figures 2-4 which involves the amplitude and energy of the waves reflected back into and transmitted out of the icefield.

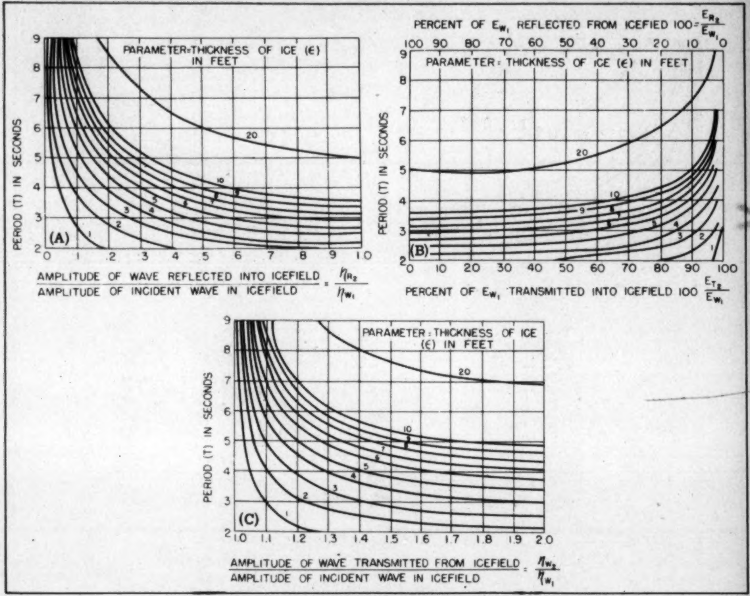

Fig. 3--Incident angle in icefield, $\theta w_1 = 0°$
($\theta w_2 = 0°$ for all T and ϵ)

Problem (c)--Equation (7) is incompatible with (14) in that (14) contains an exponential term. It is therefore obvious that the sum of the reflected and transmitted energy cannot equal the incident energy. This difficulty can be resolved by the consideration of the nature of the transmitted energy. In (10) we have considered only that portion of the transmitted energy which manifests itself in wave energy in the icefield. In actuality, it can be assumed that there exists another component of the transmitted energy which manifests itself in a pressure exerted against the overlying icefield. This may be considered as an effect due to the mass inertia of the ice. Equation (10) then becomes

$$ET_1/Ew_o = EP_1/Ew_o + \eta w_1^2 \lambda w_1 / \eta w_o^2 \lambda w_o \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(10a)}$$

where

$$EP_1/Ew_o = 4\,(\alpha^2 - K^2)^{1/2}\,(\beta^2 - K^2)^{1/2}\,(1 - e^{-2\alpha\epsilon})/[(\alpha^2 - K^2)^{1/2} + (\beta^2 - K^2)^{1/2}]^2$$

And in the case of the wave transmitted out of the icefield

$$EP_2/Ew_1 = 4\,(\alpha'^2 - K'^2)^{1/2}(\beta'^2 - K'^2)^{1/2}\,(1 - e^{2\beta'\epsilon})/[(\alpha'^2 - K'^2)^{1/2} + (\beta'^2 - K'^2)]^2 \quad \ldots \text{(18)}$$

Results--The following results were obtained.

(1) Figure 2(B) gives the per cent energy transmitted and reflected by the icefield for an incident angle of 0°. The figure shows that for a given ice thickness more energy is reflected and less transmitted for decreasing periods, while for a fixed period and increasing ice thickness less energy is transmitted. For normal incidence it is also shown from Figure 2(B) that for ice thick-

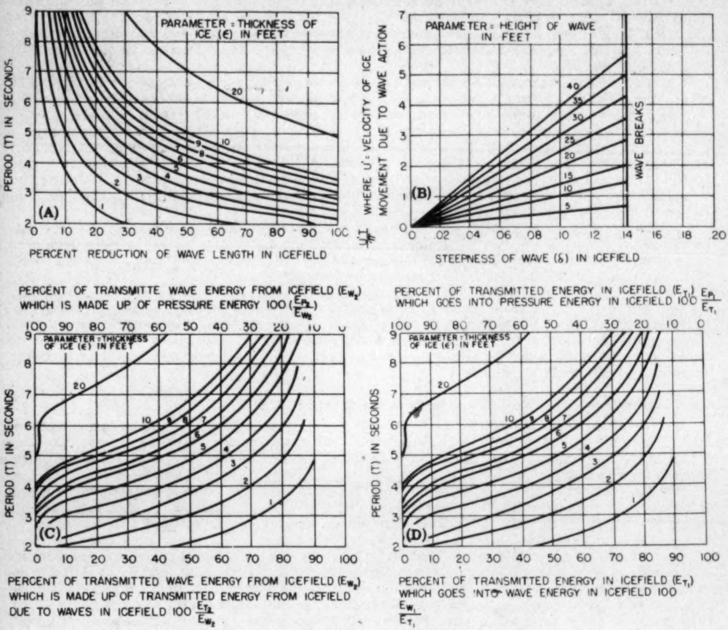

Fig. 4--Effects of the icefield

nesses up to ten feet wave periods of greater than five seconds have more than 90 pct of their energy transmitted. This result indicates that swell will generally penetrate most icefields. Computations show that, for increasing angles of incidence, less energy is transmitted.

(2) Figure 4(C) shows the percentage of the transmitted energy that goes into wave energy and pressure energy for varying wave periods and ice thicknesses. It is to be noted that these percentages are independent of the incident angle. For a given wave period and increasing ice thicknesses, less of the transmitted energy goes into wave energy, while for a given ice thickness and decreasing periods less of the transmitted energy becomes wave energy.

(3) The curves showing the transmission coefficient $\eta w_1/\eta w_0$ behave similarly to the curves showing the percentage energy transmitted 100 ET_1/Ew_0. This can be observed from Figure 2(B)-2(C). Likewise the curves showing the reflection coefficient $\eta R_1/\eta w_0$ behave similarly to the curves showing the percentage energy reflected 100 ER_1/Ew_0 (Fig. 2(A)-2(B)).

(4) For a given period and incident angle, incident waves entering an icefield are refracted less for thinner ice. Similarly, for a given angle of incidence and a given ice thickness, incident waves of increasing period are refracted less.

(5) Wave lengths in the icefield are shorter than that in the open water as is shown by Figure 4(A). This reduction is proportional to the thickness of the ice.

(6) The wave energy which is transmitted out of the icefield Ew_2 is divided into two parts, that which is transmitted from the incident wave energy in the icefield ET_2 and that which is made up of the transmitted pressure energy coming from the icefield ($-EP_2$). Figure 4(D) shows 100 ET_2/Ew_2 and 100 EP_2/Ew_2.

(7) The incident wave energy in the icefield Ew_1 is divided into two parts, that which is transmitted out of the icefield ET_2 and that which is reflected into the icefield ER_2. The curves showing 100 ET_2/Ew_1 behave similarly to the curves showing 100 ET_1/Ew_o and the curves showing 100 ER_2/Ew_1 behave similarly to the curves showing 100 ER_1/Ew_o. This can be seen from Figures 2(B) and 3(B).

(8) Figure 3(C) shows that for normal incidence $\eta w_2/\eta w_1$ is ≥ 1 as contrasted to Figure 2(C) where $\eta w_1/\eta w_o \leq 1$. This is due to the fact that in the former case pressure energy is added to ET_2 to give Ew_2 while in the latter case pressure energy is subtracted from ET_1 to give Ew_1. However, in the case of angles of incidence other than 0°, $\eta w_2/\eta w_1$ is not necessarily always greater than or equal to unity. This is due to the effect of total reflection caused by the existence of a critical angle which tends to diminish $\eta w_2/\eta w_1$ to 0. For a given angle of incidence in the icefield and for a given ice thickness, $\eta w_2/\eta w_1 = 0$ for a sufficient small period. As the period increases, $\eta w_2/\eta w_1$ increases to a maximum value greater than unity and, with further increases in period, decreases and approaches unity.

(9) The curves showing $\eta R_2/\eta w_1$ are similar to the curves showing $\eta R_1/\eta w_o$, for normal incidence the curves being identical (compare Fig. 2(A) and 3(A)). For a given angle of incidence other than 0° and for a given period and thickness of ice $\eta R_2/\eta w_1 > \eta R_2/\eta w_o$. This is caused by the existance of the critical angle at the second boundary.

(10) The angle of refraction is less than the angle of incidence for water waves entering an icefield and is greater than the angle of incidence for water waves leaving an icefield (analogous to light waves entering and leaving a denser medium). For a given angle of incidence and a given period in the icefield, the angle of refraction leaving the icefield increases for increasing ice thicknesses, while for a given angle of incidence and given ice thickness the angle of refraction decreases with increasing period.

Conclusions--The following conclusions are drawn.

(1) Waves entering an icefield are damped by two main processes: (a) The pressure cushioning effect due to the structural differences between ice and water and therefore the masses that are affected by the wave motion. (b) The multiple reflection processes that take place at the boundaries between ice and water.

(2) The icefield acts as a filter which tends to select the period of wave energy which can be transmitted through the icefield. In general, if a wave train approaches an icefield, those waves having the larger periods are most likely to penetrate deepest into the icefield with the highest percentage of their original energy.

(3) For arbitrarily small ice thicknesses, waves of sufficiently small period can not exist in an icefield. Waves of large enough period which enter the icefield may be slightly modified by the wind component which is in the same direction to that of the wave propagation. However, if there is a wind component opposing the wave propagation in the icefield, it seems likely in general that rapid damping of the wave will occur. Future study on the regeneration of waves by winds in an icefield is needed to determine accurately the modifications that may occur.

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WATER WAVE REFLECTION DUE TO SURFACE TENSION AND FLOATING ICE

Josep~~h B. Keller~~ and Edward Goldstein

Abstract--In this paper two distinct but related problems are considered: the reflection of water waves from a region covered by floating matter, and the reflection of water waves from a region having an appreciable surface tension. The results are obtained from shallow water theory on the supposition that the depth is small compared to the wavelength.

Introduction--Water waves are partly reflected when incident upon a region of the surface which has an appreciable surface tension or which is covered by floating matter. The floating matter which we consider is assumed to be a flexible mat or a distribution of separate mass points, and is supposed to represent a broken ice field or a debris-covered region. The case of appreciable surface tension is supposed to represent a thin sheet of canvas or other material tightly stretched over the surface. Such sheets have been proposed as possible aircraft landing strips for use on the ocean. Thus part of the present investigation may be of use in evaluating the feasibility of such proposals.

We assume that half the surface is free, while the other half either has an appreciable surface tension or is covered by floating matter, or both. Waves incident from the free surface are partly reflected by the "unfree" surface. We obtain the reflection coefficient provided that the amplitude of the motion is small so that the linear theory is applicable, and that the depth is small compared to the wavelength so that the shallow water theory applies. The case of floating matter was previously treated for finite depth (that is, without the shallow water assumption) by **KELLER** and **WEITZ** [1950] and for infinite depth by **PETERS** [1950]. Thus the present case of floating matter is included in the results of Keller and Weitz, but the formulas given there require extensive computations in order to yield numerical results. The formulas of the present article, on the other hand, are completely elementary. This simplicity is compensated by the limitation of the present results to water shallow compared to a wavelength.

Formulation--We consider the irrotational motion of an incompressible, inviscid fluid over a rigid horizontal bottom. The flow may be described by a potential function $\phi\,(x,y,z,t)$ which satisfies

$$\nabla^2\phi = 0 \qquad (1)$$

$$\phi_y = 0 \quad \text{at} \quad y = 0 \qquad (2)$$

$$\eta_t - \phi_x\,\eta_x - \phi_z\,\eta_z = -\phi_y \quad \text{at} \quad y = h + \eta(x,z,t) \qquad (3)$$

In these equations $y = h + \eta(x,z,t)$ is the equation of the surface, where h is its equilibrium position and y is positive upwards.

The pressure p is given by Bernoulli's equation

$$-p/\rho = (\nabla\phi)^2/2 - \phi_t + g(y - h) \qquad (4)$$

where ρ is density and g is the acceleration of gravity.

In addition to (1) to (3) a dynamic condition relating the pressure p in the fluid and the pressure p_A above the fluid must be imposed. If the surface is free, with neither floating matter nor surface tension, these pressures must be equal.

$$p = p_A \quad \text{at} \quad y = h + \eta(x,z,t) \quad [\text{free surface}] \qquad (5)$$

On the other hand, if the surface is covered by floating matter of mass m per unit area and if the surface has surface tension T, then the pressure difference is partly balanced by surface tension, and the unbalanced pressure force accelerates the mass. Thus we have from Newton's law, if θ is the angle between the outward surface normal and the vertical,

$$(p - p_A + T\eta_{xx} + T\eta_{zz})\cos\theta - mg = m\eta_{tt} \quad \text{at} \quad y = h + \eta(x,z,t) \tag{6}$$

We assume that p_A is constant, and take it to be zero since only pressure differences occur in the problem. Then (1) to (4) and (6) constitute the equations for the determination of ϕ and η, if m and T are given, as well as appropriate initial conditions and conditions at infinity.

To simplify the problem we introduce the two assumptions of small motion (linearization) and of shallow depth (compared to a wavelength). According to the first assumption, we neglect all non-linear terms in η and ϕ. Then (1) and (2) remain unchanged, while (3) and (6) become, upon making use of (4),

$$\eta_t = -\phi_y \quad \text{at} \quad y = h \tag{7}$$

$$-\phi_t + g\eta = (T/\rho)(\eta_{xx} + \eta_{zz}) - (m/\rho)\,\eta_{tt} - mg/\rho \quad \text{at } y = h \tag{8}$$

If (8) is differentiated with respect to t and use made of (7), (8) becomes

$$\phi_{tt} + g\phi_y = (T/\rho)(\phi_{yxx} + \phi_{yzz}) - (m/\rho)\,\phi_{ytt} \quad \text{at} \quad y = h \tag{9}$$

Equations (1), (2), and (9) determine ϕ, and (7) yields η.

In employing the second assumption, that of shallow depth, we first expand ϕ in powers of y, and find from (1) and (2) that ϕ may be expressed in terms of a function f (x,z,t) by

$$\phi(x,y,z,t) = f(x,z,t) - y^2(f_{xx} + f_{zz})/2 + \ldots \tag{10}$$

If we compute ϕ_y from (10), then neglecting second-order terms in h we have

$$\phi_y = -h(f_{xx} + f_{zz}) = -h(\phi_{xx} + \phi_{zz}) \quad \text{at} \quad y = h \tag{11}$$

From (9) and (11) we finally obtain an equation for ϕ at y = h

$$\phi_{tt} - gh(\phi_{xx} + \phi_{zz}) = -(hT/\rho)(\phi_{xxxx} + 2\phi_{xxzz} + \phi_{zzzz}) + (hm/\rho)(\phi_{xxtt} + \phi_{zztt}) \tag{12}$$

This is the basic equation of the linearized shallow water theory, as modified by the presence of surface tension and floating matter. If both T and m are zero, (12) becomes the usual equation of the linearized shallow water theory. In the remaining sections we will consider solutions of this equation.

Plane waves--Let us seek a time harmonic plane wave solution of (12) of the form

$$\phi = e^{i\omega t + ik(x\cos\theta + z\sin\theta)} \tag{13}$$

Insertion of (13) into (12) yields the following biquadratic for k

$$hT/\rho\, k^4 + h(g - m\omega^2/\rho)\,k^2 - \omega^2 = 0 \tag{14}$$

This has the four solutions

$$k_{\pm}^2 = \frac{\omega^2}{gh(1 - m\omega^2/\rho g)}\left[\frac{-1 \pm \sqrt{1 + 4\alpha}}{2\alpha}\right] \tag{15}$$

where

$$\alpha = \frac{\omega^2 T}{\rho g^2 h(1 - m\omega^2/\rho g)^2} \tag{16}$$

Thus k_+^2 is positive, and yields two waves propagating in opposite directions provided $m\omega^2/\rho g < 1$, while k_-^2 is negative and yields damped waves in this case. Conversely, if $m\omega^2/\rho g > 1$, k_+^2 is negative and k_-^2 positive. As α (or T) approaches zero, these solutions approach

$$k_+^2 = \frac{\omega^2}{gh(1 - m\omega^2/\rho g)} \tag{17}$$

$$k_-^2 = \frac{\omega^2}{gh(1 - m\omega^2/\rho g)} \cdot \frac{1}{\alpha} = \pm\infty \quad \text{as} \quad m\omega^2/\rho g \gtrless 1 \quad \ldots\ldots\ldots\ldots\ (18)$$

When $m\omega^2/\rho g < 1$, the k_+ waves still propagate in the limit, while the k_- modes vanish. If $m\omega^2/\rho g > 1$, the k_+ modes remain damped in the limit, while the k_- waves have no limit, oscillating infinitely often. In this case the limit problem ($\alpha = 0$) has no propagating waves and two damped k_+ modes. These limit results apply in the absence of surface tension ($T = 0$), and only the first case occurs for a free surface ($m = T = 0$). In fact, when $T = 0$, (14) becomes a quadratic and has the two roots given by (17), which in turn reduce to $\pm\,\omega/\sqrt{gh}$ for the free surface case $m = 0$.

Reflection of waves due to surface tension--Suppose half the surface ($x < 0$) is free (that is, $T = m = 0$), while on the other half T is not zero and m is arbitrary. We assume that a plane wave of the form indicated by (13) is incident from the free side, and seek the reflected and transmitted waves. It is clear that a single reflected plane wave will arise, as well as one propagating wave and one decaying mode transmitted into the "unfree" side. The other two possibilities are excluded since one propagates in from the right, while the other becomes infinite as x approaches $+\infty$.

Formally we have (with $-\pi/2 < \theta < \pi/2$)

$$\phi = e^{i\omega[t - (1/\sqrt{gh})(x\cos\theta + z\sin\theta)]} + R\,e^{i\omega[t + (1/\sqrt{gh})(x\cos\theta' + z\sin\theta')]} \qquad x < 0\ \ldots\ (19)$$

$$\phi = S_+\,e^{i\omega t - ik_+(x\cos\theta'' + z\sin\theta'')} + S_-\,e^{i\omega t + ik_-(x\cos\theta''' + z\sin\theta''')} \qquad x > 0\ \ldots\ldots\ (20)$$

The reflection coefficient R and the two transmission coefficients S_+, S_- are to be determined, as well as the angle of reflection θ' and the two angles of refraction θ'', θ'''. The roots $-k_+$ and $+k_-$ were chosen on the assumption that $m\omega^2/\rho g < 1$ and therefore k_+ is real and positive, k_- is positive imaginary. If $m\omega^2/\rho g > 1$, we replace k_+ by $-k_+$ and k_- by $-k_-$.

In order to determine the unknown constants, we make use of the conditions of conservation of mass and energy, which must apply at the plane $x = 0$ between the two regions. Consistent with our previous assumptions, these conditions imply that ϕ, ϕ_x, and $\phi_{xx} + \phi_{zz}$ be continuous at $x = 0$. Applying these three conditons to (19) and (20) yields

$$e^{-(i\omega/\sqrt{gh})\,z\sin\theta} + R\,e^{(i\omega/\sqrt{gh})\,z\sin\theta'} = S_+\,e^{-ik_+z\sin\theta''} + S_-\,e^{ik_-z\sin\theta'''}\ \ldots\ (21)$$

$$(i\omega/\sqrt{gh})[-\cos\theta\, e^{(-i\omega/\sqrt{gh})\,z\sin\theta} + R\cos\theta'\, e^{(i\omega/\sqrt{gh})\,z\sin\theta'}]$$
$$= -ik_+\,S_+\cos\theta''\,e^{-ik_+z\sin\theta''} + ik_-\,S_-\cos\theta''\,e^{ik_-z\sin\theta'''}\ \ldots\ldots\ldots\ (22)$$

$$(-\omega^2/gh)\ [\cos^2\theta\ e^{(-i\omega/\sqrt{gh})\,z\sin\theta} + R\cos^2\theta'\,e^{(i\omega/\sqrt{gh})\,z\sin\theta'}]$$
$$= -k_+^2\cos^2\theta''\,S_+\,e^{-ik_+z\sin\theta''} - k_-^2\cos^2\theta''\,S_-\,e^{ik_-z\sin\theta'''}\ \ldots\ldots\ldots\ (23)$$

Since these are identities in z, we obtain conditions which determine the angles

$$-(i\omega/\sqrt{gh})\sin\theta = (i\omega/\sqrt{gh})\sin\theta' = -ik_+\sin\theta'' = ik_-\sin\theta'''\ \ldots\ldots\ldots\ (24)$$

From (24) we see that $\theta' = -\theta$, the law of reflection, and for θ'', θ''' we have the law of refraction

$$\sin\theta''/\sin\theta = \omega/(k_+\sqrt{gh}) \qquad \sin\theta'''/\sin\theta = \omega/(k_-\sqrt{gh})\ \ldots\ldots\ldots\ (25)$$

As we have assumed that k_+ is positive, the first equation has a real solution θ'' between $\pm\,\pi/2$ provided $\omega\sin\theta/k_+\sqrt{gh} \leq 1$, and none otherwise. In this latter case, which is one of total reflection, we have from (25)

$$k_+\cos\theta'' = -(k_+^2 - \omega^2\sin^2\theta/gh)^{1/2} = -i\,(\omega^2\sin^2\theta/gh - k_+^2)^{1/2}\ \ldots\ldots\ (26)$$

Thus the k_+ wave is also exponentially decaying in this case. In the same way

$$k_- \cos\theta''' = (k_-^2 - \omega^2 \sin^2\theta/gh)^{1/2} = i\,(\omega^2 \sin^2\theta/gh - k_-^2)^{1/2} \qquad (27)$$

Now the exponential functions of z in (21) to (23) may be cancelled since they are all equal by (24), and we obtain three inhomogeneous linear equations for R, S_+, S_-. We shall evaluate only the reflection coefficient R. Introducing the abbreviations

$$k_1 = k_+ (\omega/\sqrt{gh})^{-1} \qquad k_2 = ik_- (\omega/\sqrt{gh})^{-1} \qquad (28)$$

we find

$$R = \frac{-k_1^2\cos\theta\cos^2\theta'' + k_1\cos^2\theta\cos\theta'' - k_2^2\cos^2\theta'''(-k_1\cos'' + \cos\theta) + ik_2\cos\theta'''(-k_1\cos^2\theta'' + \cos^2\theta)}{-k_1^2\cos\theta'\cos^2\theta'' - k_1\cos^2\theta'\cos\theta'' - k_2^2\cos^2\theta'''(k_1\cos\theta'' + \cos\theta') + ik_2\cos\theta'''(k_1^2\cos^2\theta'' - \cos^2\theta')} \qquad (29)$$

In the special case of normal incidence ($\theta = 0$), (24) yields $\theta' = \theta'' = \theta''' = 0$, in which case all the cosines in (29) are equal to one. The absolute value and phase angle ψ of R may then be written in the forms

$$R = -\frac{[(A^2+B^2-C^2)^2 + 4A^2C^2]^{1/2}}{A^2 + (B+C)^2} e^{i\psi} = \frac{1-k_1}{1+k_1} e^{i\psi} \qquad (30)$$

$$\tan\psi = -2AC/(A^2 + B^2 - C^2) = -2k_2/1 - k_2^2 \qquad (31)$$

where

$$A = k_2(1 - k_1^2) \qquad B = k_1(1 + k_2^2) \qquad C = k_1^2 + k_2^2 \qquad (32)$$

The roots k_1, k_2 defined by (28) and (15) depend upon two dimensionless parameters only: α given by (16), and $m\omega^2/\rho g$. Thus R depends only upon these two parameters. Graphs of $|R|$ and ψ as functions of α for $m\omega^2/\rho g = 0$ (that is, $m = 0$) and $\theta = 0$ are given in Figures 1 and 2. In this case, for large α (30) and (31) yield $|R| \approx 1 - 2/\sqrt[4]{\alpha}$, $\tan\psi \approx 2/\sqrt[4]{\alpha}$.

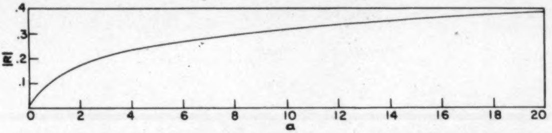

Fig. 1--Relation of reflection coefficient to $\alpha = \omega^2 T/\rho g^2 h$; the absolute value of the reflection coefficient due to surface tension, as a function of α, for normal incidence, ($\theta = 0$) and no floating matter ($m = 0$)

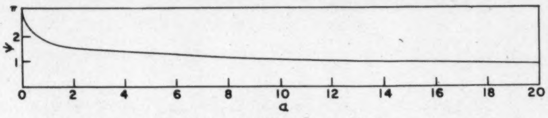

Fig. 2--Relation of phase angle to $\alpha = \omega^2 T/\rho g^2 h$; the phase angle of the reflection coefficient due to surface tension, as a function of α, for normal incidence, ($\theta = 0$) and no floating matter ($m = 0$)

Reflection of waves due to floating matter--We now consider the case in which half the surface ($x < 0$) is free, as before, while on the other half T is zero but m is not zero. In other words, floating matter is present, but there is no surface tension. This case may be treated just as the previous case was, and it is in fact much simpler since now (14) is a quadratic and therefore only two waves can occur, both of the k_+ type. Thus in (20) the coefficient S_- is zero, since no wave of that type exists. At $x = 0$ only ϕ and ϕ_x can be made continuous since (12) for ϕ is only of second order in x. Thus only (21) and (22), with $S_- = 0$, would be obtained for the determination of R and S_+.

From (21) and (22), we find, provided $m\omega^2/\rho g < 1$,

$$R = \frac{\cos\theta - k_+ (\omega/\sqrt{gh})^{-1} \cos\theta''}{\cos\theta' + k_+ (\omega/\sqrt{gh})^{-1} \cos\theta''} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (33)$$

From the exponentials in z, we again conclude $\theta = -\theta'$ and $\sin\theta''/\sin\theta = \omega/k_+\sqrt{gh}$. Letting $k_1 = k_+ (\omega/\sqrt{gh})^{-1}$, (33) may be written in the form

$$R = \frac{\cos\theta - \sqrt{k_1^2 - \sin^2\theta}}{\cos\theta + \sqrt{k_1^2 - \sin^2\theta}} \qquad m\omega^2/\rho g < 1 \ldots\ldots\ldots\ldots\ldots\ldots \quad (34)$$

where

$$k_1^2 = (1 - m\omega^2/\rho g)^{-1} > 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (35)$$

Equations (34) and (35) show that R is real and negative.

If $m\omega^2/\rho g > 1$, (33) holds provided k_+ is changed to $-k_+$, as explained after (20). Then we define k_1 by

$$k_1 = -ik_+ (\omega/\sqrt{gh})^{-1} = (m\omega^2/\rho g - 1)^{-1/2} \quad \ldots\ldots\ldots\ldots\ldots \quad (36)$$

and (33) can be written

$$R = \frac{\cos\theta - ik_1\cos\theta''}{\cos\theta + ik_1\cos\theta''} = e^{i\psi} \qquad m\omega^2/\rho g > 1 \ldots\ldots\ldots \quad (37)$$

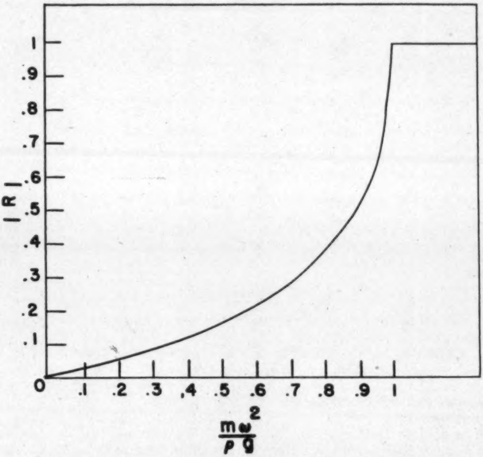

Fig. 3--Relationship between $m\omega^2/\rho g$ and reflection coefficient; the absolute value of the reflection coefficient due to floating matter, as a function of $m\omega^2/\rho g$, for normal incidence ($\theta = 0$) and no surface tension ($T = 0$)

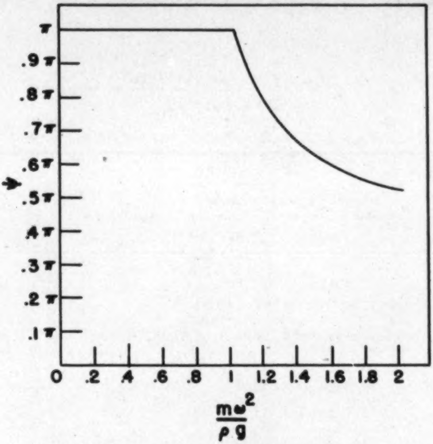

Fig. 4--The phase angle of the reflection coefficient due to floating matter, as a function of $m\omega^2/\rho g$, for normal incidence ($\theta = 0$) and no surface tension ($T = 0$)

The phase angle ψ is given by (using the equation above for θ'')

$$\tan \psi = \frac{(\sin^2\theta + k_1^2)^{1/2} \cos \theta}{\cos^2\theta - \sin^2\theta - k_1^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (38)$$

From (37) we see that $|R| = 1$, corresponding to total reflection.

The reflection coefficient depends only upon θ and the dimensionless ratio $m\omega^2/\rho g$. Equations (34) or (37) and (38) apply according as this ratio is less or greater than one. Graphs of $|R|$ and ψ as functions of this ratio are given in Figures 3 and 4 for normal incidence, $\theta = 0$.

The above results are also easily obtained from (29) by passing to the limit $T = 0$.

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ACCURACY OF DETERMINATION OF ANNUAL PRECIPITATION OVER A GIVEN AREA

Earl E. Sanderson and Don O. Johnstone

Abstract--The limits within which the total precipitation as measured by a single gage represents the total precipitation over the surrounding area is a subject of great interest to hydrologists and meteorologists. The lack of adequate data from large areas has made detailed analytical studies impossible. The precipitation-gage network established during the period from 1935 to 1940 in the Muskingum River Watershed in Ohio by the U. S. Soil Conservation Service provides data for limited studies for a 8038-sq mi area. Records from 230 gages for a full year beginning October 1, 1939, are available. The data from these stations have been used by the authors to analyze the effect of gage spacing on the accuracy of determination of the amount of annual precipitation for areas in Ohio ranging in size from a few square miles to 8000 sq mi.

Introduction--In the analysis of the data presented in Bulletin 15 of the OHIO DIVISION OF WATER [1950], a study was made to determine the limits within which the total annual precipitation as measured by a single gage or by a group of gages represents the total annual precipitation over the surrounding area. The study was made by Don O. Johnstone, at that time Assistant Professor in the Department of Civil Engineering, Ohio State University. For detailed study, the Muskingum Watershed Conservancy District records for the water year 1939-40 were chosen.

The Muskingum Basin with an area of 8038 sq mi (see Fig. 1) comprises about one-fifth the total area of the State, and the areal distribution of rainfall over it is at least as non-uniform as in other portions of the State except for an area in the southwestern part where the long-time average annual rainfall varies as much as ten inches between points less than 30 mi apart. The Army - Navy - NACA - Weather Bureau Cloud-Physics Project in the vicinity of Wilmington, Ohio, was located in the latter area (see Fig. 1). The average annual precipitation at Wilmington for the 25-year period 1921-45 is about eight inches greater than the State average and about ten inches greater than the averages for the same period at Dayton and Springfield, 30 mi to the north, and eight inches greater than at Cincinnati, 40 mi to the southwest. The data studied by LINSLEY and KOHLER [1951] were recorded in an area noted for its thunderstorm activity and high annual precipitation.

The water year 1939-40 was fairly representative of average conditions. Records for the full year were available from 230 gages. For more than half of these gages it was necessary to estimate rainfall for a few scattered days in order to complete the record. These estimates were made from the detailed daily isohyetal maps prepared by the Muskingum Watershed Conservancy District. If nearby gages indicated that the rainfall for a missing day was unevenly distributed, it was arbitrarily assumed that the error in the estimate was half the difference between the reported precipitation at the two nearest gages. No gages for which the sum of the "errors" for all missing days of the year amounted to more than 1.5 inches were used in the study. Actually only eight of them had errors of as much as one inch.

The first reaction was to treat the gages as a random sample and define the standard error of the mean as $\bar{\sigma}/\sqrt{n}$, in which $\bar{\sigma}$ is the estimated standard deviation in the universe and n is the number of gages.

$$\bar{\sigma} = \sigma\sqrt{n/(n-1)}$$

where σ is the standard deviation of the sample computed from the formula

$$\sigma = \sqrt{\Sigma x^2/n}$$

where x represents the difference of any individual item from the mean. There are at least two objections to such a procedure. (1) Estimates of accuracy are often needed for areas represented by only one gage, or at best by a very small number of gages, in which case the formula is either totally inapplicable or highly questionable. (2) The sample provided by the gages may actually be better or worse than a random sample. If it is better, the formula underestimates the accuracy,

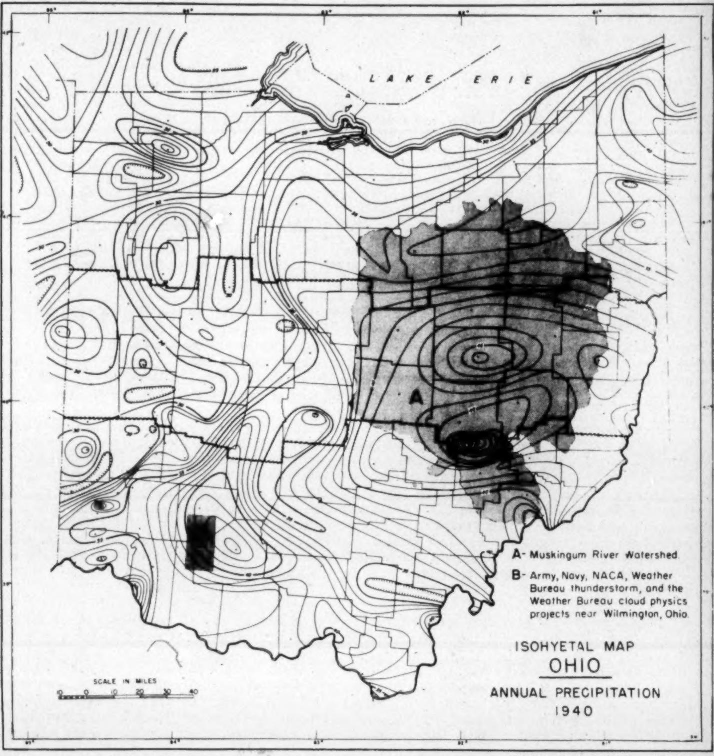
LAKE ERIE
A
A- Muskingum River Watershed
B- Army, Navy, NACA, Weather Bureau thunderstorm, and the Weather Bureau cloud physics projects near Wilmington, Ohio
ISOHYETAL MAP
OHIO
ANNUAL PRECIPITATION
1940
SCALE IN MILES
10 0 10 20 30 40

Fig. 1--Isohyetal map of Ohio showing locations of precipitation study areas

and if worse, it gives too optimistic a result. A method was, therefore, sought that would take these two objections into account.

Precipitation amount as measured by a single gage

If over an area of A square miles the actual standard deviation of total annual precipitation is $\overline{\sigma}$ inches, then we may say *a priori* that the chances are two out of three that a gage spotted at random in the area yields a catch within $\overline{\sigma}$ inches of the true mean for the area. This is only another way of saying that the *a priori* standard error with which a single gage chosen at random represents the rainfall over the surrounding A square miles is $\overline{\sigma}$ inches. If there is found to be a significant relationship between A and $\overline{\sigma}$, the resulting curve will provide a partial answer to the question.

Seven subareas were laid out to represent hypothetical drainage basins containing at least 30 gages each, with no intentional relation to topography. The unweighted mean precipitation was

Table 1--Results of analysis of unweighted mean precipitation for seven subareas

Item	Designation	Area	Number of gages	Mean precipitation	σ	$\bar{\sigma}$
		sq mi		inch		
1	Total	8038	230	38.62	3.41	3.42
2	A	982	31	37.03	4.10	4.17
3	B	834	32	38.14	3.18	3.23
4	C	1345	32	39.27	2.89	2.94
5	D	1408	31	40.01	3.22	3.27
6	E	1183	30	41.15	3.14	3.19
7	F	933	30	38.74	2.70	2.74
8	G	1071	37	36.61	2.43	2.47
9	Mean, A-G	1108	..	....	...	3.14 ±0.23

then computed for the total area and for each of the seven subareas, together with the standard deviations of the samples and the estimated standard deviations in the universe. The results are shown in Table 1.

Items 1 and 9 supply two plotting points for the curve. To find the standard deviation of rainfall over smaller areas, a different method had to be adopted, as there were not enough gages in individual small areas to provide usable samples. Accordingly, some 50 gages were chosen at random over the basin and around each was drawn a circle enclosing an area of 113 sq mi (radius six miles). Within these circles lay a total of 175 gages in addition to those at the centers. The difference between the total annual precipitation at each of these outlying gages and the total annual precipitation at its central gage was then computed and the 175 resulting items were divided into six groups on the basis of total precipitation at the central gages. Standard deviations were then computed as before, with results shown in Table 2.

Table 2--Results of precipitation analysis based on circular areas

Item	Precipitation at center	Number of observations	σ	$\bar{\sigma}$
	inch			
1	42.3 to 45.9	31	2.54	2.58
2	40.5 to 42.0	30	2.06	2.09
3	38.6 to 39.6	30	1.98	2.01
4	37.3 to 38.1	30	2.71	2.75
5	35.1 to 37.1	29	2.56	2.60
6	29.6 to 34.9	25	2.47	2.52
7	Mean	..	...	2.42 ±0.13

Item 7 provides a third plotting point. By similar methods a fourth point was computed for circular areas of 28 sq mi, except that in this case only 60 items were used and the sample was not broken down into subgroups. The value of $\bar{\sigma}$ was 2.41; its standard error could not be computed.

For still smaller areas, records of a concentrated group of 12 gages in the North Appalachian Experimental Watershed were used. (In this case the data are for the calendar year 1939.) Values of $\bar{\sigma}$ of 1.28 and 1.55 inches were found for areas of three and 16 sq mi respectively. These points are recognized as weak, but they help to give direction to the lower end of the curve, and they lie beyond the range with which most of the later discussion is concerned.

The six points computed by the various methods just described were plotted in Figure 2 and a curve was fitted to them by eye. Primarily this curve shows the standard deviation of rainfall that occurred over areas of various sizes in the Muskingum Valley in 1939-40.

It is assumed, within reasonable limits, that this is representative of the standard deviation of precipitation that can be expected in areas of similar size throughout Ohio, and in other years than 1939-40. The curve also represents the a priori standard error with which a single gage chosen at random represents the precipitation over an area of given size. Nothing in the study

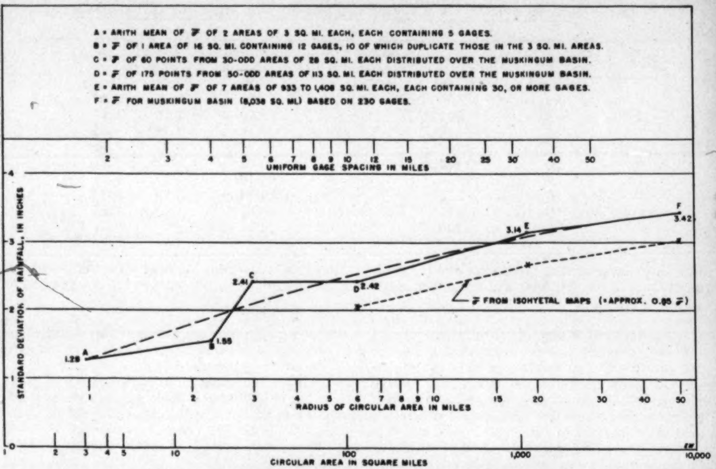

Fig. 2--Standard deviation of rainfall over areas of various sizes in the Muskingum Valley, water year 1939-40

provided a basis for the determination of the actual standard error of a specific gage. "Actual standard error with which a specific gage measures precipitation in the surrounding area" probably has significance only in case the "surrounding area is meteorologically homogeneous"; such an assumption has not been made in the analysis, and can not be made for areas the size of those with which the study was concerned. The data from the curve can be applied to groups of gages to compute the standard error with which the group measures total precipitation over a given area in a given year. It can not be applied to a specific gage over a period of years to compute the standard error with which that gage measures the mean annual precipitation over the surrounding area.

Precipitation amount as measured by a group of gages--We are now in a position to evaluate the accuracy with which a group of gages measures the annual precipitation amount over a given area A. The catches of the n gages constitute an n-item sample of an essentially infinite universe. But this universe is not statistically homogeneous, since, as shown by Figure 2, the standard deviations for individual subareas (that is, subuniverses) are less than the standard deviation for the area as a whole. If then we consider that the catch at each gage represents the annual precipitation amount in the surrounding subarea a with a standard error equal to the standard deviation of precipitation $\bar{\sigma}$ over that subarea, the precipitation amount over the whole area, as given by the mean of n gages, has a standard error of

$$\bar{\sigma}_M = \sqrt{a_1^2\bar{\sigma}_1^2 + a_2^2\bar{\sigma}_2^2 + \ldots + a_n^2\bar{\sigma}_n^2}/A \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

If the gages are equally spaced, $a_1 = a_2 = \ldots = a_n$, $\bar{\sigma}_1 = \bar{\sigma}_2 = \ldots = \bar{\sigma}_n$, and (1) becomes

$$\bar{\sigma}_M = \sqrt{na^2\bar{\sigma}_{A/n}^2}/na = \bar{\sigma}_{A/n}/\sqrt{n} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

in which the symbol $\bar{\sigma}_{A/n}$ is used to denote $\bar{\sigma}$, as read from Figure 2 for an area equal to A/n.

Since the value of $\bar{\sigma}_{A/n}$ is less than the value of $\bar{\sigma}_A$, it is obvious from (2) that equally spaced gages provide a better-than-random sample of the universe. To take a specific example, consider an area of 150 sq mi in which five gages are located. From Figure 2 $\bar{\sigma}_{150}$ = 2.60 inches. If the

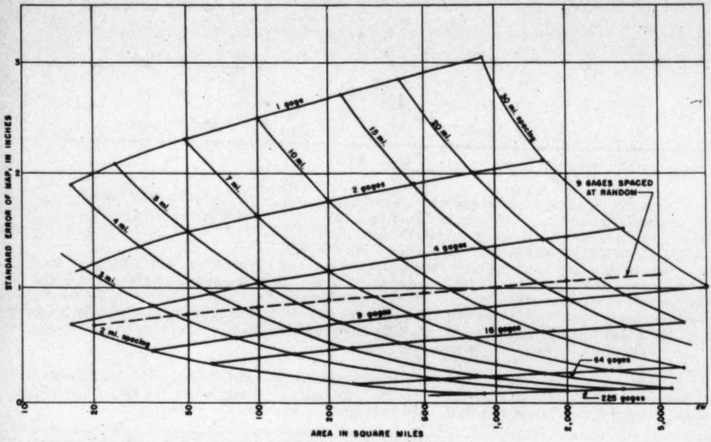

Fig. 3--Standard error of isohyetal map for areas of various sizes with various spacings of gages

gages constituted no better than a random sample, the standard error in determination of the precipitation amount over the whole area would be 1.16 inches. However, with the gages uniformly spaced, each of them would represent an area of A/n = 30 sq mi; and since $\bar{\sigma}_{30}$ = 2.15 inches, the standard error of the determination would reduce to $2.15/\sqrt{5}$ = 0.96 inch. Figure 3 is a solution of (2) for various values of A and n.

As we depart further and further from uniform spacing, the sample provided by the gages tends to become truly random, and, ultimately, "worse than random." Eq. (1) permits us to evaluate any particular group of irregularly spaced gages. For a specific example, let us refer again to the 150-sq mi area with its group of five gages, but assume now that the gage spacing is such as to give THIESSEN [1911] coefficients of 10, 20, 30, 40, and 50 sq mi, respectively. Reading values of $\bar{\sigma}$ from Figure 2 and substituting in (1), we find the standard error to be 1.105 inches, which is worse than the standard error of a uniformly-spaced group, though still not so poor as that of a purely random group. Assuming next that the Thiessen coefficients are 10, 10, 40, 40, and 50, the standard error becomes 1.16 inches. In other words, this particular spacing proves to be one of many that amount to truly random samples of the total area. Finally, with Thiessen coefficients of 10, 10, 30, 50, and 50, we obtain a standard error of 1.19 inches, indicating that the gages have now become so irregularly spaced that their results are no longer as reliable as those of even a random sample.

The practical importance of obtaining uniformity in gage spacing is indicated by the dotted line in Figure 3, which shows the standard error for a random sample of nine gages. Insofar as measuring the annual precipitation amount is concerned, it appears that the same accuracy would be obtainable with from five to seven equally spaced gages as with nine so spaced as to constitute a random sample. No attention is given in this study to the number of gages required to measure, with a specified degree of accuracy, the precipitation over shorter periods than a year.

Accuracy of isohyetal maps

General--In the preceding section, methods were developed for computing the accuracy with which groups of gages of either regular or irregular spacing measure the annual precipitation amount over areas of various sizes. These methods are applicable to computations made with Thiessen coefficients. The question remains whether computations made from carefully prepared isohyetal maps can be considered as of any higher order of accuracy.

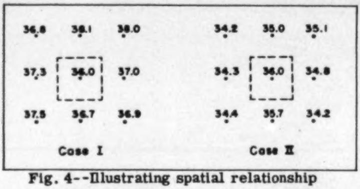

Fig. 4--Illustrating spatial relationship

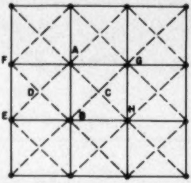

Fig. 5--Basic gage lines and diamonds of an isohyetal map

Certainly the maps themselves take into account one factor that is ignored in a Thiessen computation. This factor, which we shall call "spatial relationship," can best be illustrated by an example. In Figure 4 are shown two areas of the same size, each containing one gage and surrounded by eight others. In each of the two areas, the gage reads 36 inches, and so using the Thiessen method we would attribute the same rainfall to both areas. Yet the spatial relationship, that is, the evidence of the surrounding gages, strongly suggests that the precipitation over this central area is greater than 36 inches in Case I and less than 36 inches in Case II. The isohyetal map gives weight to such evidence and provides different answers for the two cases.

In what follows, an attempt has been made to evaluate the accuracy of an isohyetal map for the specific case of uniform gage spacing. The standard error with which the map measures the annual precipitation amount at a point chosen at random was first evaluated.

Standard error at a random point--In Figure 5 the gages are equally spaced, and adjacent gages are joined by solid lines. It is along such lines that points on isohyetals are established by straight-line interpolation. Between points so established the isohyetals are faired in by eye, "giving reasonable consideration to the evidence of other nearby gages." Thus in the diamond ACBD, straight-line interpolation along the gage line AB is the primary consideration in locating the isohyetals. However, the isohyetals are not constructed simply as perpendiculars to this line. In the area ABD consideration is given also to the precipitation amounts recorded at E and F, and the isohyetal is bent accordingly. Similarly in ACB weight is given to records of G and H. In general, then, all points within ACBD should be of about the same order of accuracy as points along, or close to, the gage line AB.

To determine how far precipitation at a point is likely to depart from the value given by straight-line interpolation, a study was made of some 240 points located along or near gage lines chosen at random in the Muskingum Basin. For each point the following basic procedure was used: (1) Scale the distance between the extreme gages and the distance from one of these gages to the intermediate gage. (2) Compute the precipitation at the location of the intermediate gage by straight-line interpolation. (3) Compute the difference between this value and the actual precipitation at the point. The data for the individual points were then assembled in seven groups according to the spacing of the extreme gages. For each group, or sample, the standard deviation was computed. The seven points were then plotted, and a curve fitted to them by eye (Fig. 6). The curve thus shows the standard deviation of precipitation from the straight-line assumption for any given spacing of gages, and its ordinate may be interpreted either as the standard error of a random point on the isohyetal map or the standard error with which the isohyetals measure the precipitation over the area between two gages. It may be argued that the error near the midpoint of a gage line should be greater than that near the ends. To a certain extent this is true. However, if the samples are segregated into "quarterpoint data" and "midpoint data," no very significant difference appears between the two groups. Why this is so is illustrated by Figure 7. Whatever the distribution of precipitation between A and B, it is not a smooth arc like (a), but an arc on which more or less irregular, saw-tooth variations are superimposed, as in (b). Thus points close to A and B may depart from the assumed straight-line relationship almost as much as points near the center.

Theoretical standard error of precipitation amount over a given area

If the isohyetal map measures precipitation over the diamond-shaped area between two gages with the standard error shown by Figure 6, then the standard error for an area made up of m such diamonds all of equal size is $\overline{\sigma}/m$. For a square area with equally spaced gages the number of

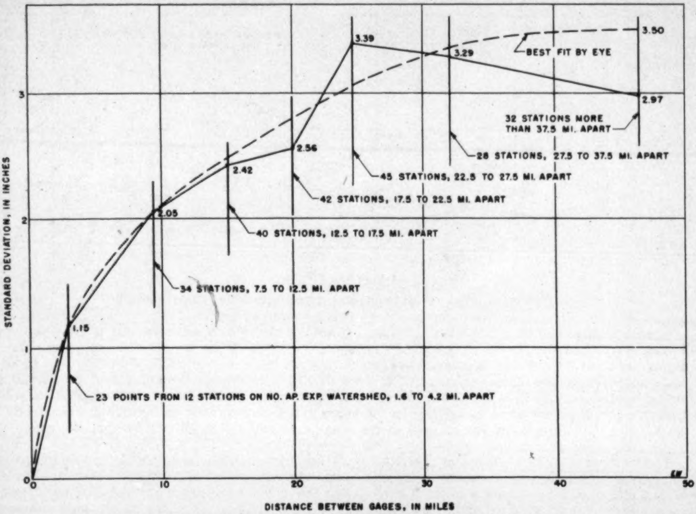

Fig. 6--Standard deviation of intermediate points from a straight line; summary

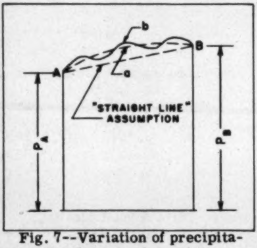

Fig. 7--Variation of precipitation between two points

diamonds is $2\sqrt{n}\,(\sqrt{n} - 1)$, where n is the number of gages. Figure 8 is a solution of $\bar{\sigma}_M = \bar{\sigma}/\sqrt{m}$ for various numbers and spacings of gages.

The dotted line in Figure 8 shows the standard error of a precipitation determination made by the Thiessen method for an area containing nine equally spaced gages. Comparison of this line with the solid nine-gage line shows how much more accurate a determination can be made from the same basic data with the aid of an isohyetal map, that is, when the "spatial relationship" factor is taken into account.

A practical assumption--The method employed for determining the standard error of an isohyetal map does not permit of extension to the case of non-uniform spacing. However, it seems reasonable to assume that non-uniform spacing has more or less the same percentage effect on the standard error of an isohyetal map as it has on the standard error of a Thiessen determination for the same area and the same number of gages. For the case of pure random spacing the standard error of the Thiessen determination is easily computed. Applying the same percentage effect to the standard errors previously determined for the "ideal" isohyetal map we arrive at values that should express reasonably well the standard error of an isohyetal map that is prepared from gages spaced so irregularly as to amount to no better than a random sample. To illustrate: Assume an area of 900 sq mi containing 16 gages. If the spacing is uniform, a Thiessen computation has a standard error of 0.62 inch. If the spacing is such as to produce a random sample, the standard error is 0.79 inch. This is 127 pct of the standard error for uniform spacing. Now for an ideal isohyetal map of the same area the standard error is 0.43 inch. Multiplying this value by 127 pct to allow for the effect of irregular gage spacing, the standard error becomes 0.55 inch.

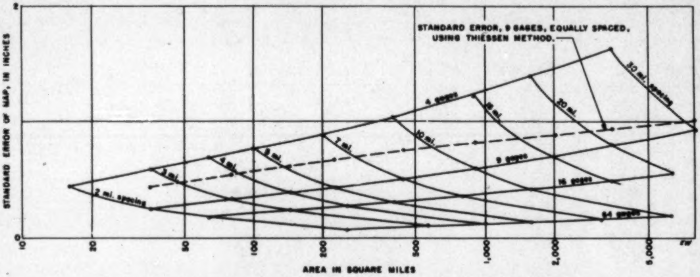

Fig. 8--Standard error of isohyetal maps with ideal gage spacing

It will be observed that this value is less, but only slightly less, than that for a Thiessen computation that is based on uniform spacing. The same was found to be true of all important combinations of area and number of gages covered by this study. In other words, the increase in accuracy achieved by use of the isohyetal map tends to offset the decrease in accuracy that results from irregular gage spacing to such an extent that the results obtained from an isohyetal map based on gages spaced "at random" are of the same order of accuracy as the results obtained from a Thiessen computation for an area of the same size containing uniformly spaced gages.

Limitations of study--The results of this study must be considered as highly approximate insofar as specific numerical values are concerned. The data on which they are based are limited, and the individual samples are small. It is possible that a more thorough analysis, using larger samples drawn from more extensive data would alter considerably the numerical values indicated in Figures 3, 4, 7, and 8. It does appear that the data are sufficient to support the basic conclusions, and that the figures referred to are at least a fair qualitative indication of what might be expected from a more thorough study.

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DISCUSSION

Walter T. Wilson (U. S. Weather Bureau, Washington 25, D. C.)--Sanderson and Johnstone are to be congratulated on their original and significant contribution to our growing knowledge of areal variability of precipitation. Areal variability of precipitation is caused by many influences which may conveniently be grouped into two major factors. One factor is the varying storm experience of the several stations in a small area. The other factor is the difference in physical exposure of the gages at these stations.

The variability caused by different storm experience may be very nearly eliminated over a small area by examining a long record, expressed as the mean annual precipitation pattern. The standard deviation of the mean annual precipitation pattern is thus a measure of the constant-with-time terrain parameters. An analysis such as the authors' could be made of the mean annual pattern and the results compared with those for the one-year total. Also, as the authors suggest, such analyses could be made for individual storms. In addition to distinguishing between the weather and the terrain parameters, the weather parameters could thus be further related to a genetic classification of storm types. For example, greater variability would be found associated with convective rainfall than with precipitation coming from stratiform clouds.

The influences classified as terrain factors can also be broken down. For example, a distinction can be made between the large-scale orographic influences and the small-scale local gage exposure. To illustrate, it is generally known that a gage exposed on a ridge usually catches less rain than does a gage in a nearby meadow. Efforts should be made to determine how much of this difference is due to the effects of the terrain on the distribution of natural precipitation, and how much is due to the performance of the gage itself in an updraft environment.

A time seems to be approaching when it will be possible to define objectively degrees of orographic and of meteorological homogeneity, and when the results of studies such as this one by Sanderson and Johnstone can be transferred from place to place in terms of reliable parameters.

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WATER QUALITY PROBLEMS IN CALIFORNIA

Harvey O. Banks and Jack H. Lawrence

Abstract--This paper discusses a few of the many serious and complex water quality problems confronting water users in California. For ease of presentation and discussion, these water quality problems are broadly grouped under conditions of pollution caused by sewage and industrial waste disposal, and degradation caused by man's development and use of the water itself. Minor quality of water problems resulting from natural causes are also recognized and discussed.

Introduction--It has long been a matter of common knowledge that pollution and degradation of water from multiple sources and causes exist throughout the State, often to an alarming degree. These conditions, although some have existed for many years, were brought sharply into focus by the phenomenal industrial development and tremendous increase in population which occurred during and subsequent to World War II and is still taking place. Local pollution problems have been intensified and great apprehension exists on the part of water users over the threat to the quality of their vital water supplies from unreasonable practices accompanying usage of the water and in waste disposal. This concern is most intense in areas wherein critical water shortages already exist. In some of these areas, reductions in usable water supplies due to conditions of deterioration in quality have been of such magnitude as to constitute a serious threat to the economy and general welfare.

Current state-wide water resources investigations--The State Water Resources Board, through the Division of Water Resources, is now conducting a state-wide water investigation. The objective is preparation of a plan for full conservation, control, protection, and utilization of the State's water resources, both surface and underground, to meet present and future needs for all beneficial purposes and uses in all areas of the State, insofar as practicable. These studies have progressed sufficiently to reach the conclusion that the States's water resources, including California's rights in the Colorado River, may be adequately regulated in available surface reservoir sites and ground-water basins to meet its probable ultimate water requirements without importation of water from a source outside the State of California, such as the Columbia River. It is to be noted that this conclusion is based on maintenance of usability in perpetuity of the ground-water basins as reservoirs for fresh water storage. This poses major unsolved water quality problems.

The Division of Water Resources is also engaged in an investigation of the quality of all of the water resources of the State, including saline waters, coastal and inland, as related to all sources of pollution and degradation of whatever nature, including damage to quality of underground waters due to abandoned, defective, and improperly constructed wells. Objective is the protection or improvement of the quality of the State's water resources for present and planned beneficial uses thereof, or both. A corollary objective is the development of techniques and plans for the maintenance of the utility of ground-water basins as underground storage reservoirs.

Native quality of the State's water resources--Before dealing specifically with water quality problems, it may be well to first consider briefly the inherent or natural quality characteristics of the native fresh waters in California. Information on this subject has been obtained from a review of many thousands of antecedent mineral analyses of water samples collected from the streams and underground reservoirs of the State. Many of the analyses were obtained from files and published reports of the Division of Water Resources. Many analyses have also been obtained from the files and published reports of state and federal agencies including the University of California and the U. S. Department of Agriculture, Regional Salinity Laboratory, and the Ground Water Branch of the U. S. Geological Survey.

Examination of these published and unpublished analyses indicate that most fresh waters in California, both surface and underground, are of excellent mineral quality and are well suited for nearly all beneficial uses without prior treatment except that for domestic and municipal use some softening and purification may be necessary. Surface and ground waters draining from the North Coastal Area, the eastern side of the Central Valley Area, and the western segment of the Coast Range Mountains are of especially good quality. Analyses show that the surface and underground

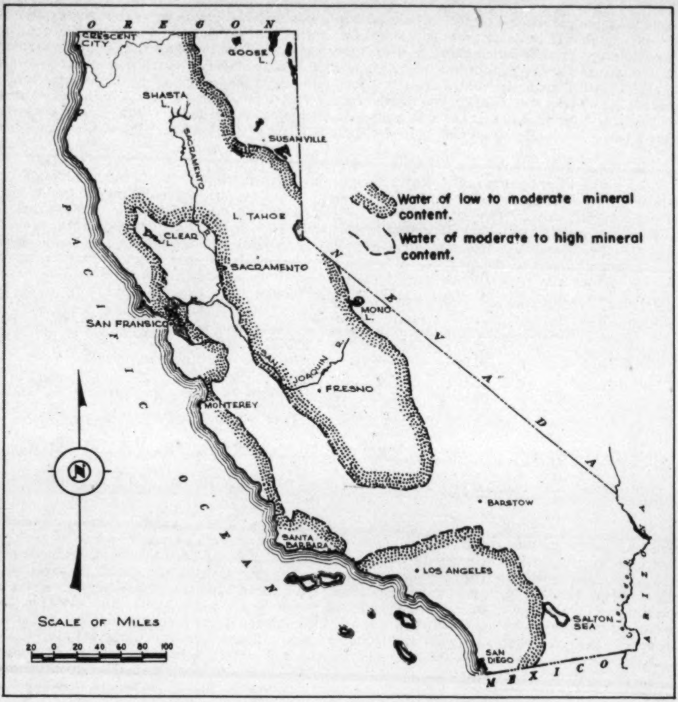
O R E G O N
CRESCENT CITY
GOOSE L.
SHASTA L.
SACRAMENTO
SUSANVILLE
Water of low to moderate mineral content.
Water of moderate to high mineral content.
L. TAHOE
CLEAR L.
SACRAMENTO
N E V A D A
MONO L.
SAN FRANSICO
P A C I F I C
O C E A N
SAN JOAQUIN R.
FRESNO
MONTEREY
BARSTOW
SANTA BARBARA
LOS ANGELES
SCALE OF MILES
20 0 20 40 60 80 100
SALTON SEA
SAN DIEGO
ARIZONA
Colorado R.
M E X I C O

Fig. 1--Quality of native fresh water in California

waters in these three broad areas possess very low concentrations of mineral solubles and hardness, low per cent sodium, and relatively small amounts of boron. These waters are of the bicarbonate type, and calcium is the predominating base constituent. In contrast, waters of comparatively high salinity occur in the west side of the Central Valley from the Cache Creek drainage area in the Sacramento Valley south to the Tehachapi area in the southern part of San Joaquin Valley. Native waters of inferior quality also occur in basins on the west slope of the Diablo Range that separates the Central Coastal and Central Valley areas, in Cuyama and Santa Maria River basins in the Central Coastal Area, Ventura River basin, and in Piru and Sespe Creeks in the South Coastal Area. Local areas of very poor water also occur in the Modoc Plateau and throughout the Lahontan and Colorado River basins. Mineral solubles in these latter waters frequently include significant amounts of boron. Other constituents, including trace elements such as fluorides, may also be present in large quantities. Large bodies of poor quality connate water also occur at relatively great depth in most of the coastal ground-water valleys and basins and under almost the entire area of the Central Valley. The last-named type of water is discussed more fully in a later paragraph. Figure 1 shows generalized water quality characteristics of the native fresh waters in California.

Investigations have shown that the inherent quality characteristics of the native fresh-water supplies, which have just been summarized, are mainly correlated with climate and geologic complex. The supplies having least amounts of mineral impurities in general are produced in areas having the greatest amount of precipitation and in areas underlain by igneous rock materials. In contrast, relatively large amounts of mineral impurities are contained in waters which occur in areas characterized by one or more of the following factors: low precipitation, interior drainage, poorly consolidated deposits of marine origin, and fault zones through which mineralized juvenile and recirculating meteoric waters are introduced into drainage and ground-water basins. It is generally found true that rainfall governs the concentration of mineral solubles in the water through the effects of dilution, and that the kind and proportion of mineral solubles in the water are governed by the types of minerals composing the rock materials and soils with which the water comes in contact.

These effects of climate and geologic complex are illustrated in Table 1, which compares analyses of water samples collected from streams in areas having different climatic conditions and geologic complexes. The water in the American River reflects conditions of abundant precipitation and runoff from areas composed largely of igneous rock materials. The water in the Cuyama River reflects conditions of comparatively low rainfall and runoff from areas composed of poorly consolidated sandstones and shale into which mineralized juvenile and recirculating meteoric waters may have entered through fault zones. Note the wide variation in both the concentration and composition of mineral solubles in the waters of the two streams.

Table 1--*Analysis of surface-water samples from two locations*

Stream	Concentrations of mineral constituents												Total	
	Ca		Mg		Na		HCO_3		Cl		SO_4			
	ppm	pct	ppm	pct	ppm	pct	ppm	pct	ppm	pct	ppm	pct	ppm	pct
American River at Fair Oaks Bridge	3	25	1	9	2	16	18	43	1	2	2	5	27	100
Cuyama River near Santa Maria	150	21	70	16	120	13	300	13	70	5	590	32	1300	100

Major causes and sources of pollution and degradation--Any significant variation in chemical properties of the surface and ground waters of the State, not correlated with climatic or geologic conditions, may usually be attributed either to pollution from sewage and industrial waste disposal or to degradation resulting from development, use, and re-use of the water itself. In some instances, degradation of quality of water may result from natural causes. These major causes of pollution and degradation of the water resources of the State are discussed in some detail in the succeeding paragraphs of this paper. Throughout the discussion, the term "pollution" means impairment of the quality due to sewage and industrial waste disposal in accordance with legislative definition, whereas degradation, unless otherwise modified, refers to impairment caused by man's development and use of the water and other resources. Table 2 presents in outline form the major sources and causes of damage to the quality of water resources. It is by no means complete insofar as the listing of industrial wastes is concerned.

Pollution of surface waters, general--The principal cause of pollution of the surface-water resources of the State is use of the waterways for disposal of sewage and industrial wastes. These wastes may broadly be classed as of two general types, (1) organic and (2) inorganic. Organic wastes are a putrescible type of pollutant principally associated with domestic sewage and with wastes from food-processing establishments such as canneries and slaughterhouses. Inorganic wastes are not subject to the processes of putrefaction that characterize the decompositon of organic substances. Some of the more important sources of inorganic or mineral wastes are the petroleum-producing industries, chemical-producing industries, industries using chemical process waters such as boron waters used in processing citrus fruit, mines, and lumber-processing industries. These latter-named industries may also have wastes high in organic matter.

Organic pollution of surface waters--Organic solids occurring in domestic sewage present problems with respect to both contamination (danger to the public health) and pollution of the waterways into which disposal is made. This is especially true when sewage-treatment plants either are lacking or do not provide sufficient treatment to the sewage. Overloading of the sewage-treatment plants by various food-processing industries is also a frequent cause of pollution, particularly during peak periods of the canning season. The manner in which the processes of organic pollution occur are explained in the following paragraph together with a description of the results of such pollution.

Table 2--Causes of damage to quality of water resources

Pollution

- 1. Domestic sewage
- 2. Industrial wastes[a]
  - A. Organic wastes
    - (1) Food processing
      - (a) Fruit and vegetable canneries
      - (b) Fish canneries and fish reduction plants
      - (c) Slaughtering plants
      - (d) Wineries
      - (e) Breweries
    - (2) Lumber processing
      - (a) Mill ponds
  - B. Mineral wastes
    - (1) Metal-processing industries
      - (a) Plating works
      - (b) Steel mills
    - (2) Mining and ore extraction industries
      - (a) Drainage from mines
      - (b) Water from processing ores
      - (c) Dredging
    - (3) Oil industries
      - (a) Drilling wastes
      - (b) Production wastes, brines, oils
      - (c) Refinery wastes
      - (d) Terminal loading wastes
      - (e) Abandoned oil and gas wells
    - (4) Chemical industries
    - (5) Miscellaneous
  - C. Cooling water
- 3. Solid and semi-solid refuse

Degradation

- 1. Effects of development, use, and re-use of water
  - A. Irrigation return
    - (1) Surface drainage
    - (2) Percolation
  - B. Interchange between aquifers due to improperly constructed, defective, or abandoned wells
  - C. Interchange between aquifers due to differentials in pressure levels resulting from excess withdrawal
  - D. Overdraft conditions
    - (1) Sea-water intrusion
    - (2) Salt balance
    - (3) Upward or lateral diffusion of connate brines due to overpumping
- 2. Natural causes
  - A. Inflow or percolation of water from highly mineralized springs and streams, or both
- 3. Other causes
  - A. Accelerated erosion

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[a] This is not intended to be a complete listing of industrial wastes that may cause trouble.

Aside from the presence of pathogenic organisms, putrescible organic matter is the principal pollutant contained in domestic sewage and in wastes from canneries and food- and beverage-processing industries. Oxygen in the receiving waters is consumed as these materials are reduced by bacterial or biochemical action into inactive humus-like materials. Unless the rate of reoxygenation is high, the waters will become less and less suitable for swimming and other recreational uses and for fish and other forms of aquatic life. Finally, if all oxygen is consumed, putrefaction of the organic waste materials occurs. The waters become septic and odorous, and fish and other beneficial aquatic life forms cannot exist. Under conditions of gross pollution, suitability of the water for all uses, including aesthetic values, is greatly reduced, and the water loses all value for fish life and recreational purposes.

In numerous bodies of water in the State, many instances may be cited in which conditions of gross pollution occur, particularly during peak periods of the canning season. Outstanding examples of conditions of pollution have occurred in the lower reaches of the Tuolumne River near Modesto, the San Joaquin River near Stockton, in the southern part of San Francisco Bay and tributary sloughs near Santa Clara and San Jose, in the Richmond-Berkeley and Emeryville areas touching upon San Francisco Bay, and in San Pablo Bay. Putrefactive odors resulting from anaerobic decomposition of the organic wastes are quite noticeable in those areas during much of the year. Fortunately, some of the more extreme conditions of pollution are being rectified by the construction of adequate sewage-treatment facilities.

Inorganic pollution of surface waters--Unlike most organic wastes, which are susceptible to removal by ordinary treatment processes, or by the natural processes of self-purification of water, the soluble chemicals or minerals comprising the inorganic wastes generally remain in the water. Their effects are diminished only by dilution, although it is possible that some chemical reactions may occur in which some compounds are changed to insoluble forms and settle out of the water.

Wastes from the oil-producing industries are considered to be one of the important sources or potential sources of pollution from the standpoint of both liquid volume and of total amount of mineral pollutant therein contained. These wastes are predominantly composed of the highly mineralized salt waters that were originally combined with the pumped oil, although incomplete oil and water separation processes may also cause some of the crude oil to be an important waste product of the oil industries.

The Thirty-Sixth Annual Report of the State Oil and Gas Supervisor shows in tabular form that the volume of waste brines produced in 1950 by the oil wells is about 510,000,000 barrels or 66,000 ac ft. The amount of dissolved minerals contained in these wastes is indicated by mineral analyses to be of the order of 1,782,000 tons. The proportion of these wastes that are discharged into the waterways of the State, however, is presently unknown. Methods of disposal, other than surface discharge, include lined and unlined sumps and evaporation ponds. In some instances, the wastes are temporarily stored and conveyed in trucks or by pipe line to the ocean or other disposal sites. In certain of the oil fields, much of the water is returned underground by injection wells under the supervision of the Division of Oil and Gas which is charged with the responsibility that no pollution will thereby accrue to usable fresh-water supplies. The latter two methods of disposal of waste waters are considered to be satisfactory from the standpoint of protection of the quality of fresh-water supplies, but the use of sumps and evaporation ponds may cause pollution of underground-water supplies. Progress is being made in correction of condition of pollution caused by oil industrial wastes.

Chemical-producing industries, or industries using chemical process waters, have, in the past, discharged large quantities of highly obnoxious and toxic plant wastes directly into the waterways of the State. This practice is being curtailed. In areas where the waste-treatment facilities are inadequate or in instances where use of the municipally-owned sewerage system is denied because of the type of wastes produced, disposal into the waterways is frequently resorted to. Industries use the Los Angeles River for waste disposal throughout the reach from San Fernando Valley to the ocean. The types of waste discharged includes phenolic compounds, formaldehyde, wastes from plastic manufacturing plants, acid wastes, and many other types of chemical wastes from manufacturing plants. It is believed that percolation of these wastes may be responsible for conditions of pollution occurring in the upper strata of ground water downstream from the unlined portion of the river channel.

Mine drainage wastes are especially important in California due to the large number of mines that are located in the mountains adjacent to stream channels. Liquid wastes from mines in many cases are composed largely of deeply circulating meteoric waters. Extreme variability is shown by mine waste waters both in mineral composition and in concentrations of total solubles. The variations are dependent upon the types of ore-bearing rocks with which the waters are associated, the relative proportion of meteoric and juvenile waters contained in the mixture, the depths to which the meteoric waters descend and the extent to which they become heated before returning to the surface. The outstanding characteristic of mine waste waters, for which analyses are readily available, is their abnormally high content of constituents such as iron, boron, and fluoride, which occur only in trace amounts in native fresh-water supplies. An additional characteristic of certain of the mine-waste waters is high acidity which is in large part due to the formation of sulphuric acid from the oxidation of iron sulphide. Due to the highly deleterious and toxic nature of the wastes, only small quantities of mine drainage are required to cause pollution of the waterway into which it is discharged. The volume of the mine-waste waters and the quantity of dissolved minerals therein contained have not been ascertained for all of the various types of mines occurring in California. Information in the files of the State Division of Water Resources shows that drainage from a quick-silver mine located on the slopes of Mount Diablo has a pH of 2.5 and contains about 57,000 ppm of dissolved solids, which include 121 ppm of boron, 2640 ppm of iron, and 340 ppm of aluminum.

Water that has percolated through mine-tailing dumps frequently contains large amounts of suspended materials and dissolved minerals which, when added to stream flow, are extremely harmful or toxic to fish life. Ore-processing wastes, such as finely ground rock and cyanides that are discharged into the streams, are similarly harmful.

Widespread deleterious effects on fish life have been reported as being due to miscellaneous types of wastes discharged from lumber and lumber-processing industries. Such industries frequently contribute to pollution of stream flow by discharging therein large amounts of sawdust pulp and organic and inorganic process wastes such as sulfites. Water in log ponds usually contains large quantities of tannin and is also considered to be an important source of pollution to surface waters in lumbering areas.

Degradation of surface water--Degradation has previously been defined as being an impairment to quality of water that is caused by the development, use, and re-use of the water itself. In the case of surface water, one cause of such impairment is the inflow from irrigation drainage. Irrigation drainage water may contain as much as 4000 ppm or more of total dissolved solids and these are a major degradant to certain surface waters during periods of low flow. Nearly all major streams which pass through areas of irrigated agriculture receive return flow either as effluent seepage or as surface drainage. The adverse effects of irrigation return on a given stream are marked by the increase in the content of total solubles with distance of flow of the stream from the mountains. Irrigation drainage also results in a marked change in the composition of surface flow in that there is generally an increase in the proportion of sodium chloride salinity. These changes may be observed by comparing the analyses of water collected from various points on the San Joaquin River between Mendota and Vernalis (see Table 3). This reach of the river receives both irrigation drainage and effluent seepage from the ground water during the irrigation season together with large amounts of inflow from tributary streams draining the Sierra Nevada. Regardless of the inflow from the tributary streams, the increase in total mineral solubles in the water between the upper and lower reaches is high.

Table 3--Effect of ground-water inflow and irrigation return on quality of water in San Joaquin River

Sampling point	Stream mile	Date 1950	Flow cfs	Chloride ppm	Total solids ppm
At Mendota Pool	208	6/20	426	3.8	34
At Temple Slough	187	6/20	421.7	3.5	35
At Fremont Ford	130	6/23	156	120	420
Above mouth of Merced River	124	6/23	194	170	570
Below mouth of Merced River	123	6/23	428	84	320
Near West Stanislaus irrigation district diversion[a]	91.8	6/24	. . .	120	460
Near Vernalis[b]	76.7	6/24	947	110	370

[a] Above Tuolumne and Stanislaus Rivers.

[b] Below Tuolumne and Stanislaus Rivers.

Another important cause of degradation to quality of surface flow is erosional detritus. This degradant consists largely of suspended particles of silt and clay and is derived in varying amounts from all areas of the watershed through natural processes of weathering and erosion. Erosional detritus is nearly always a natural characteristic of stream flow, but man's activities frequently add to the load carried by the streams. Accelerated erosion due to cultivation and gravel-pit operations in or near stream beds are cases in point. Erosional detritus is considered to be an important degradant because of the importance of its effect on water uses and water-treatment processes as well as its effect upon the siltation of reservoirs. Turbidity and silt in water are quite harmful also to fish life, clogging the gills and affecting hatching of fish eggs.

Natural degradation of the quality of water in the streams of California frequently results from the intermingling of waters that possess different mineralogical characteristics. Numerous instances may be cited where a water of low mineral content in one stream is degraded by the inflow of a highly mineralized water from tributary stream. The degradant or degradants in the water of the offending tributary are frequently traceable to contributions from mineral springs and mines or from the overflow of saline lakes. In most instances, however, the inferior quality characteristics of the water in the offending stream are attributable to the effects of climate and to the mineralogical characteristics of the rocks comprising the drainage area.

Pollution of ground water--Serious conditions of pollution of the ground-water resources occur when industrial wastes containing organic solvents and other chemical compounds are either indiscriminately discharged into open unlined sumps or directly onto a highly absorptive surface dump site area, or are disposed of directly to the ground water through wells. Land disposal of domestic sewage is widely practiced in California, but such disposal generally causes little trouble as far as pollution of ground water is concerned because the organic and bacterial components of domestic sewage are rapidly removed from the liquid phase by the filtration and purification capacity of the soil through which it moves. Thus, that portion of domestic sewage which reaches the ground water compares reasonably well with the native ground waters, depending upon the original sources of supply which are used to convey the wastes from the home. Solvents and soluble chemicals contained in industrial wastes, however, remain in solution in the liquid phase in most instances, and percolate downward to the underlying ground water.

Chemical derivatives from various sources, including oil and other petroleum fractions and plating wastes, are particularly harmful pollutants of ground water because only small amounts may be required to render the water unfit for use. An instance is the well-publicized case of the Montebello incident in Los Angeles County, wherein phenolic compounds rendered a portion of the water in Montebello Basin below Whittier Narrows unfit for use for a considerable period of time. It is reported also that the accidental dumping of a tank car of oil some 20 years ago in San Joaquin Valley still exerts an effect today.

Degradation of ground water--The following paragraphs consider impairment to quality of ground water that is caused by development and use of the water and other resources. Deterioration of quality due to this cause is generally much less spectacular or apparent than pollution caused by waste disposal, but investigations indicate that the adverse effects, both existing and potential, are much greater. A case in point is the degradation that occurs in irrigated areas through the return of deeply percolating irrigation waters. Such waters invariably carry downward with them to the underlying ground waters large amounts of dissolved minerals derived from fertilizers and displaced soil solubles. The amount of mineral solubles that may be added as a degradant to the underlying waters from these sources is extremely high. However, the extent of the damage to underground waters from this cause has not been evaluated, although there is some evidence that in the Salinas Valley and in some areas of the southern part of California the build-up in salinity of the ground water is subject to measurement. Studies are being made of this problem in those areas by the Division of Water Resources in connection with the aforementioned state-wide water quality investigation.

Principal causes of degradation of ground water are listed in Table 2 and include: (1) interchange between aquifers, (2) overdraft conditions, and (3) adverse salt balance. These three specific causes of degradation are discussed in some detail in the following pages.

Interchange between aquifers--In portions of many ground-water basins, improperly constructed, defective, and abandoned wells allow the free flow of water from one aquifer to another, thus creating problems with respect to existing or potential degradation of the water resources. The more serious of these problems occur in areas underlain by several distinct aquifers, each yielding water under a different pressure level and of differing quality characteristics. Under these conditions, it is possible for a poor quality water in one aquifer to invade and degrade the good quality water contained in another aquifer. Interchange between aquifers may also occur naturally through imperfections in the clays that confine the pressure aquifers.

Overdraft conditions--Great changes in the water-pressure levels that are caused by conditions of heavy pumping and overdraft will accelerate the interchange of water between aquifers. Overdraft may so reduce pressure levels in the principal pumping zone as to cause: (a) upward or lateral movement of locally entrapped brines of geologic origin, or both; (b) sea-water intrusion in coastal areas; and (c) downward movement of perched water.

It has previously been mentioned that connate brines underlie aquifers of good quality water in numerous ground-water valleys and basins of California, including the Central Valley. These waters originated during past geologic periods when the ground-water basins were inundated by the ocean. The ocean waters that became entrapped in the since uplifted land-form elements frequently make their appearance in water pumped from the deeper wells or from areas wherein the fresh ground-water levels are markedly lowered through overdraft. Usually, these relatively deep-seated connate brines have a considerable pressure head and readily rise to the surface, either through defective and abandoned wells or through improperly constructed wells such as those gravel-packed to full depth in poor locations. An example is cited where a well 1500 ft in depth, located near the town of Robbins in the Sacramento Valley, yields saline artesian water at a rate of about 200 gal/min. The water from this well has a concentration of mineral solubles of about 6000 ppm, a chloride concentration of 1700 ppm, and a sodium content of 75 pct.

It is not unusual for connate brines to contain as much as 30,000 or more ppm of dissolved mineral solubles. One acre foot of such water would thus contribute about 82,000 pounds of salt to the fresh-water supply with which it may be combined. It takes only a relatively small amount of these brines to seriously degrade native fresh-water supplies of good quality.

The invasion of connate brines into principal pumping zones is easily detected, especially in the heavily overdrawn ground-water reservoirs that occur in the west side of San Joaquin Valley. Heavy pumping has so reduced the fresh-water levels in this area as to permit the underlying connate brines to migrate upward in ever-increasing quantities. Many of the deep wells thus commonly yield water in which concentrations of total mineral solubles increase markedly with time of pumping. This phenomenon is illustrated in Table 4, which compares electrical conductivity measurements of a series of water samples collected from U. S. Geological Survey Well No. 14/14-7M1, a well that is located in Fresno County on the west side of the San Joaquin Valley. (The well from which the samples were obtained was in continuous operation since 07h 15m, May 18, 1951. Reported depth of the well is 1640 ft; the perforated interval is 600-1400 ft; it is gravel-packed to full depth.) An approximation of the content of total dissolved mineral solubles may be obtained by multiplying the respective conductivity values presented in Table 4 by a factor of 0.7.

Table 4--Example of increase in mineral content with pumping

Date	$K \times 10^6$ at 25°C
1951	
May 18	1500
20	1750
22	1770
24	1820
26	2020
28	2060
June 2	2080

In some of the ground-water valleys and basins, the deep-seated connate brines may invade fresh-water aquifers by natural means, such as movement through geologic fractures and faults or through natural imperfections in the confining clays. The volume of connate brines invading a particular aquifer through natural faults or imperfections is, of course, increased by pumping and subsequent reduction in pressure levels in the aquifer being invaded.

Sea-water intrusion is a very critical problem in coastal areas where ground-water extractions exceed replenishment. Investigations made by the Division of Water Resources show that degradation of fresh-water supplies from this source has occurred in 14 major and minor ground-water basins adjacent to the Pacific Ocean. As of 1950, sea-water intrusion has advanced inland in these basins, a distance of from 1/8 to four miles and much of the water underlying an area of about 90,000 acres has been rendered unfit for general use. Many wells located in the affected area were subsequently abandoned by their owners. The direct cause of sea-water intrusion in all instances may be attributed to overdraft conditions which have reversed the normal seaward slope of the water plane.

Free perched ground water commonly overlies the confining clay of pressure aquifers in portions of many coastal and inland ground-water basins. This water accumulates displaced soil solubles and unused chemicals from fertilizers and is often subject to processes of evaporation and transpiration and, in coastal areas, to inundation by tidal action. It thus may occasionally contain even more salt than ocean water. The existence of defective, improperly constructed, and abandoned wells permit the downward movement of this inferior-quality perched water into the fresh-water supplies contained in the underlying pressure aquifers.

Degradation of well-water supplies from percolating perched water is most pronounced in areas such as the west side of San Joaquin Valley where inferior-quality perched waters drain into wells that are gravel-packed to full depth. In coastal areas, old wells that have been abandoned due to the effects of sea-water intrusion permit percolation of the perched water through old, rotted casings, and thus provide a secondary source of degradation to the underlying water resources. The effects of the percolating perched water may be so pronounced in some coastal areas as to negate costly attempts to reclaim the usefulness of the aquifer by preventing sea-water intrusion.

Adverse salt balance--The conditions of pollution and degradation of ground waters described above are long-lasting and may even be permanent depending upon whether or not there is movement of water from the basin. This is in marked contrast to surface streams in which impairment of water quality may be almost immediately alleviated by flood flows or corrected by discontinuance of specific waste disposals. In many instances, however, depreciation of quality of ground water is further accentuated by unfavorable salt balance, a condition that is most pronounced in areas of overdraft where the water supply to the basin is largely utilized, or in areas where there is little or no movement of ground water from the basin. In such areas, the salinity caused by even a relatively innocuous waste may build up dangerously over a period of years, thus rendering the ground waters increasingly less suitable for beneficial uses.

Unless the adverse salt-balance conditions described above are corrected, the usefulness of the ground-water basins as reservoirs for storage of fresh water will be seriously affected. Normally, operation of the ground-water basin as a reservoir can be so planned as to protect the quality of water therein contained. Protection may be obtained by drawing down the water levels in dry periods to provide space for conservation of high-quality flood waters to reduce surface waste and hence increase ground-water outflow. Where outflow of ground water is too small to dispose of the required quantity of salts, pumping and exportation of water would accomplish the same purpose. Location of such pumping in areas of highest salinity would result in best efficiency. In planning operation of a basin to best utilize the water supply, it is essential that provision be made for enough additional supply to provide for the outflow which is necessary for protection of quality.

The problem of maintaining favorable salt balance will become increasingly important as ground-water development proceeds. At the present time, ground water supplies about 50 pct of the water used in California. Its importance cannot be overemphasized.

Summary--Critical problems have been caused by disposal of sewage and industrial wastes into the water resources of the State. Considerable progress has been and is being made in the abatement and prevention of these conditions by the State Health Department and the State and Regional Water Pollution Control Boards, aided by such other agencies as the Department of Fish and Game and the Division of Water Resources.

Water quality problems associated with or caused by the development and use of the State's water and other resources are considered to be equally serious in nature and more complex as to solution. These include:

Interchange between aquifers containing water of differing quality characteristics or downward percolation of saline perched waters through abandoned, defective, and improperly constructed wells

Interchange between aquifers or downward percolation of perched saline waters because of pressure differentials caused by withdrawal of ground water

Percolation of irrigation return containing mineral fertilizer and displaced soil solutions

Overdraft conditions which promote conditions of sea-water intrusion, adverse salt balance, and upward diffusion of connate brines

Salt balance in ground-water basins

Careful planning is necessary to preserve the utility of the State's ground-water basins.

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RAINFALL AND TOPOGRAPHIC FACTORS THAT AFFECT RUNOFF

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Abstract--Based on runoff records for the period 1938-48, peak-rate probability curves are computed for 51 watersheds located in the Allegheny-Cumberland Plateau and ranging in size from 100 to 350,000 ac. A simple correlation is computed to determine the relationship between the peak rate for a ten-year recurrence interval and area. The average standard error was 34.8 pct. Two rainfall factors representative of the period of runoff record are then introduced together with a topographic factor, and a multiple correlation is computed. The average standard error was reduced to 18.2 pct. Long-term rainfall factors are then computed and used in the multiple correlation equation to determine the peaks that would have resulted from the peak-rate probability curves had long-term runoff records been available. Relationships between ten-year peaks and those for 25- and 50-year frequencies are determined from the peak-rate probability curves and the Plateau is divided into two zones based on these relationships.

Introduction--Although long-term runoff records for 30- to 40-year periods are available for most of our principal streams, this is not true for the thousands of smaller tributaries. In fact, records of runoff from small agricultural watersheds for more than ten years are practically nonexistent. Yet the safe and economical design of the large majority of drainage structures depends on the reliability of estimates of the peak rates of runoff that may be expected from these small watersheds.

This paper describes a procedure in which easily determined rainfall and topographic factors are used to compensate for the lack of long-term runoff records and to increase the reliability of estimates of peak rates from small mixed-cover watersheds in the Allegheny-Cumberland Plateau area (Fig. 1).

Runoff data--The boundaries of the Allegheny-Cumberland Plateau are those determined by the Soil Conservation Service as a result of conservation surveys. All gaged streams within this area that had runoff records for the period 1938-48 and drained areas up to 350,000 ac were tabulated. This tabulation was then screened to exclude all streams where backwater conditions, diversions, or low-water control were found to exist. One watershed was excluded because approximately 20 pct of the area was found to be urban or industrial and two others because extensive swamps and reservoir control were found at the headwaters. After this screening there remained 51 mixed-cover watersheds with areas ranging from 100 to 350,000 ac and with runoff records of from eight to 11 years. Six of these were watersheds located in the North Appalachian Experimental Watershed [U. S. DEPARTMENT OF AGRICULTURE, 1941, 1942] and gaged by the Soil Conservation Service, and the remainder were watersheds gaged by the U. S. Geological Survey.

Relationship of peak rate of runoff and area--Probability curves of instantaneous peak rates of runoff were computed for each of the 51 watersheds in accordance with the theory of extreme values [GUMBEL, 1945; POTTER, 1949a]. The relationship between the peak rate for a ten-year recurrence interval and the area of the watershed was determined by computing a least-squares correlation. The regression equation for this correlation was

$$\log q = 0.490 - 0.299 \log A$$

where q is the ten-year peak in cubic feet per second per acre and A is the area of the watershed in acres. The standard error was found to be +40.6 pct and -28.9 pct.

Selection of factors--The large standard error for the correlation of q and A could have been occasioned by differences in vegetative cover, rainfall, or topography between the 51 watersheds. If these differences could be expressed as variables that could be easily derived from readily available data, then the reliability of peak-rate estimates would be materially increased by the inclusion of the additional variables in a multiple correlation.

Vegetative cover--Vegetative cover was divided into three classes: cropland, pasture, and woodland. Estimates of the per cent of the area in each class were furnished by the Soil Conserva-

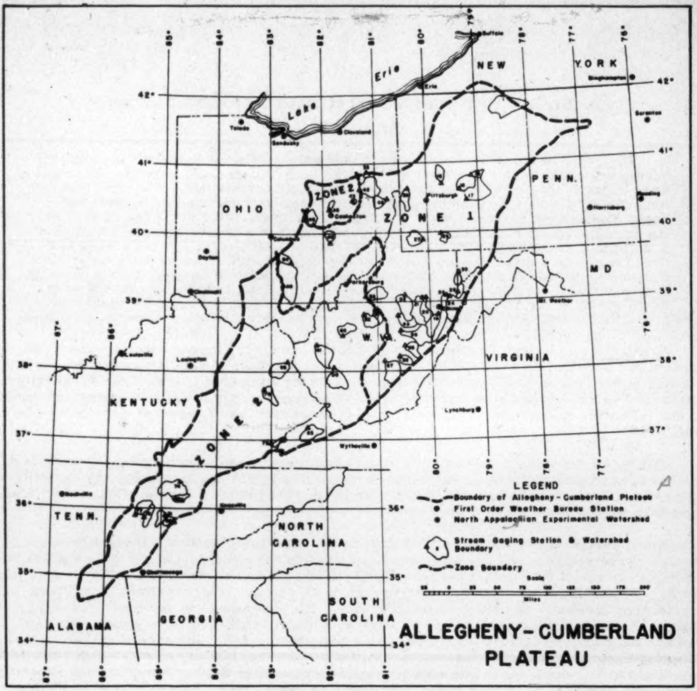
ALLEGHENY-CUMBERLAND PLATEAU
Lake Erie
NEW YORK
PENN.
OHIO
ZONE 2
ZONE 1
ZONE 3
W. VA.
MD
VIRGINIA
KENTUCKY
TENN.
NORTH CAROLINA
SOUTH CAROLINA
GEORGIA
ALABAMA
Buffalo
Erie
Toledo
Sandusky
Cleveland
Pittsburgh
Harrisburg
Columbus
Dayton
Cincinnati
Lexington
Louisville
Parkersburg
Mt. Weather
Lynchburg
Wytheville
Knoxville
Nashville
Chattanooga
Binghamton
Scranton
Reading
42°
41°
40°
39°
38°
37°
36°
35°
34°
87°
86°
85°
84°
83°
82°
81°
80°
79°
78°
77°
76°
LEGEND
Boundary of Allegheny - Cumberland Plateau
First Order Weather Bureau Station
North Appalachian Experimental Watershed
Stream Gaging Station & Watershed Boundary
Zone Boundary
Scale
Miles

Fig. 1--Allegheny-Cumberland Plateau

tion Service for each watershed. These values were tabulated, together with the per cent deviation of the ten-year peak from that derived from the regression equation of the relation of q to A. Although the amount of cropland varied between watersheds from 0 to 60 pct and the woodland from 16 to 98 pct, no significant effect of these differences on the magnitude of the ten-year peak was discernible. Many of the largest deviations above the regression value were for watersheds where the cropland was zero and the woodland was 98 pct. Likewise, many of the largest deviations below the regression value were for watersheds where the cropland was 50 to 60 pct. For this reason it was concluded that for the Allegheny-Cumberland Plateau area and for watersheds within the range of the experimental data, the magnitude of peak rates of runoff are little affected by vegetative cover when the recurrence interval is ten years or greater.

Rainfall factors--In a frequency study the magnitude of the peak rate of runoff for any recurrence interval is affected by the intensity of the rainfall experienced during the period of runoff record. Likewise, the frequency of any peak rate is affected by the product of annual rainfall and the number of excessive storms [POTTER, 1949b].

The rainfall-intensity factor was designated as the P-ratio and may be defined as the average ratio of rainfall intensity for 10-, 25-, and 50-year recurrence intervals for any particular location to similar values derived from long-term rainfall records for Columbus, Ohio. To obtain the

P-ratio for the period of runoff record (1938-48) for each of the 51 watersheds, probability curves of maximum 60-minute intensities were computed for 18 first-order Weather Bureau stations (Fig. 1), 62 stations of the Weather Bureau hydrologic network for the Ohio River District, and nine Tennessee Valley Authority stations, or for a total of 89 recording rainfall stations. For each of these stations the intensity for a 10-, 25-, and 50-year recurrence interval was expressed as a ratio of a similar value derived from the 1915-48 rainfall record for Columbus, Ohio. The average of the ratios for the three recurrence intervals was taken as the P-ratio for the rainfall station. The P-ratio for each station was then plotted on a map of the Allegheny-Cumberland Plateau and lines of equal P-ratios were drawn. From this map the P-ratio corresponding to each of the 51 watersheds was tabulated.

The frequency factor was designated as the S-ratio and may be defined as the average ratio of the product of annual rainfall and number of excessive storms for 10-, 25-, and 50-year recurrence intervals for any particular location to similar values derived from long-term rainfall records for Columbus, Ohio. S-ratios for the period of runoff record were determined for each watershed in the same manner as that described for the P-ratios. Probability curves of the product of annual rainfall and number of excessive storms were computed for each of the 89 rainfall stations. Values of this product for 10-, 25-, and 50-year recurrence intervals were expressed as ratios of similar values derived from the 1915-48 rainfall records for Columbus, Ohio. The average of the ratios for the three recurrence intervals was taken as the S-ratio for each station. A map showing lines of equal S-ratios was prepared from which the S-ratio corresponding to each watershed was tabulated.

Topographic factors--Many topographic factors other than area affect peak rates of runoff [LANGBEIN, 1947]. The measurement of all of these factors and the subsequent testing of their significance by multiple correlation and an analysis of co-variance would have been a task for an electronic computer. Even if this had been done it is considered doubtful if the resulting regression equation would have had much practical value. Designing engineers either would not have had the data available or would not have taken the time necessary to measure the many topographic factors. An attempt was made, therefore, to select some simple measure that would be indicative of the net effect of several of the principal topographic factors. The index finally selected involves only the measurement of the length and slope of the principal waterway. It was designated as the T-factor and may be defined as the length of the principal waterway divided by the square root of the channel slope. Since velocity varies as the square root of slope, the T-factor is indicative of time of channel flow. Considered with area and peak rate of runoff in a multiple correlation it is also indicative of time of concentration, channel storage, and watershed shape.

Using U. S. Geological Survey topographic maps, the length of the principal stream channel from gaging station to headwaters was measured for each of the 51 watersheds. It was found that a break in the slope of most of the stream channels occurred at approximately 0.7 of the channel length measured from the gaging station. Accordingly, the channel was divided into two reaches, one of which was 0.7 of the total length and the other the remaining three-tenths. The length of each reach, in miles, was then divided by the square root of the corresponding slope, in feet per mile, and the sum of the two quotients tabulated as the T-factor.

Multiple correlation--Having determined the rainfall and topographic factors for each of the 51 watersheds, a multiple correlation was now computed in which these factors were considered as independent variables with the ten-year peak rate of runoff the dependent variable. The regression equation for this correlation was

$$\log q = -1.421 + 0.170 \log A - 0.554 \log T + 0.929 \log P + 0.449 \log S$$

in which

q = Peak rate of runoff, in cu ft per sec per acre, for a ten-year recurrence interval
A = Area in acres
T = T-factor (topography)
P = P-ratio (rainfall intensity)
S = S-ratio (frequency)

An analysis of co-variance showed all of the independent variables to be significant beyond the 0.001 level.

The progressive reduction in the standard error as each new variable was added to the correlation is shown in Table 1.

Table 1--Effect of the addition of independent variables on standard error

Variables	Standard error		
	Upper limit	Lower limit	Average
	pct	pct	pct
q vs A	40.6	28.9	34.8
q vs A and T	34.6	25.7	30.2
q vs A, T, and P	23.4	19.0	21.2
q vs A, T, P, and S	19.9	16.6	18.2

Values of A, T, P, and S, as determined for each watershed, were introduced into the regression equation to obtain values of the theoretical peak rate of runoff. These were compared with the values determined from the peak-rate probability curves and the difference expressed as a per cent of the theoretical value (Table 2). The distribution of error that would have resulted among the 51 watersheds had q been computed by the regression equation is shown in Table 3.

An investigation of the runoff record for the 13 watersheds for which the difference between the theoretical and actual q was greater than 18 pct showed that the maximum peak rate of record for five of the watersheds had either been estimated from flood marks by the slope-area method or from a rating curve extended three times beyond the highest current meter measurement. In other words, some of the variance unexplained by the correlation could probably be ascribed to errors in the original runoff data upon which the correlation was based.

Long-term P- and S-ratios--A probability curve based on a runoff record of only 8 to 11 years is reliable only to the extent that the factors that affected runoff during that period were representative of a much longer period. If factors that are representative of a long period could be determined, then the relationships defined by the regression equation could be applied to obtain an equally representative value of q. This new q would be the value that could have been expected from the probability curve had long-term runoff records been available.

Since topographic factors for any given watershed may be considered constant, the only factors affected by the length of the period of record were the P- and S-ratios.

To obtain long-term values of the P-ratio, probability curves of 60-min rainfall intensities were computed for each of the 18 first-order Weather Bureau stations (see earlier section on rainfall factors). These curves were based on intensity records for the period 1915-48. Following the same procedure used in obtaining short-term P-ratios, values of 60-min intensity at each station for recurrence intervals of 10, 25, and 50 years were expressed as an average ratio of similar values computed from the 1915-48 intensity record for Columbus, Ohio.

Because of the mountainous terrain of the Allegheny-Cumberland Plateau, it was felt that rainfall throughout the area would be materially affected by orographic influences. Since 18 rainfall stations are too few to define the effects of these influences, a straight-line variation of the P-ratios between stations was not justified. Instead, a straight-line variation between stations was assumed for the difference between long- and short-term P-ratios expressed as a per cent of the long-term ratio. In accordance with this assumption, per cent differences between long- and short-term P-ratios were computed for each first-order station and a map was prepared showing lines of equal per cent differences. Using this map and the one showing lines of equal short-term P-ratios, values of long-term P-ratios could then be computed for any desired location by applying the equation

$$P_L = P_s/(1 - a)$$

in which P_L is the long-term P-ratio, P_s is the short-term P-ratio, and a is the per cent difference. Following this procedure, a third map was drawn to show lines of equal long-term P-ratios.

The same assumptions and procedures, described for the determination of long-term P-ratios, were used in the preparation of a map of equal long-term S-ratios. These two maps were then combined in a single map of equal values of $(P^{0.929}\ S^{0.449})$.

Table 2--Correlation variables and deviation of q from the theoretical value q_c

Watershed number	Area	T	P	S	q	$\frac{q_c - q}{q_c}$
	1000 ac					pct
10c	0.122	0.041	0.99	1.90	0.830	-24
5c	0.349	0.065	0.99	1.90	0.620	- 1
92c	0.920	0.142	0.99	1.90	0.400	+15
43	1.05	0.220	1.00	1.30	0.229	+29
94c	1.52	0.256	0.99	1.90	0.430	-16
95c	2.57	0.399	0.99	1.90	0.360	-13
97c	4.58	0.802	0.99	1.90	0.230	+ 3
35	12.0	1.76	1.02	0.95	0.140	- 2
45	17.6	2.00	1.00	1.60	0.163	+ 4
29	47.1	4.38	0.90	1.40	0.0737	+33
48	48.4	6.41	1.10	1.90	0.103	+17
72	52.5	4.33	0.95	1.40	0.151	-27
80	53.2	2.62	1.20	2.80	0.317	-19
25	55.1	5.12	0.63	1.47	0.0741	+ 2
15	56.0	5.70	0.92	1.15	0.0854	+ 7
54	56.0	6.34	0.90	1.50	0.0926	+ 3
81	59.9	4.94	1.05	2.20	0.170	-12
76	73.0	3.71	1.10	2.20	0.148	+23
82	78.7	2.27	0.95	2.50	0.211	+11
55	82.0	4.44	0.75	1.00	0.146	-67
30	85.8	6.16	0.63	1.50	0.0695	+ 7
18	87.8	7.03	0.80	1.00	0.0745	- 2
70	89.6	13.0	1.08	2.30	0.125	-27
46	89.6	8.46	0.95	1.90	0.0911	+11
40	94.8	7.94	0.90	1.20	0.0683	+18
20	95.5	7.44	0.85	1.50	0.0939	- 4
56	96.0	2.42	0.70	1.00	0.113	+ 5
49	99.0	6.66	0.75	1.50	0.0851	+ 2
51	106.0	8.46	0.95	1.60	0.103	- 5
39	114.0	12.1	0.85	1.20	0.0612	+ 5
77	114.0	9.50	1.15	2.40	0.133	+ 1
27	115.0	9.93	1.02	1.70	0.0999	0
22	116.0	15.6	0.85	1.70	0.0838	-28
19	120.0	7.92	0.87	1.20	0.0812	+ 3
16	122.0	8.16	0.90	1.00	0.0643	+18
52	131.0	8.55	0.95	1.50	0.131	-33
53	134.0	13.7	0.95	1.50	0.0866	-14
26	137.0	14.0	0.90	1.30	0.0709	- 6
66	139.0	16.8	1.15	2.30	0.0935	+ 6
60	152.0	18.8	1.10	1.40	0.0849	-17
42	163.0	10.6	0.82	1.10	0.0432	+37
59	173.0	7.14	0.95	1.00	0.127	-34
21	177.0	12.3	0.80	1.50	0.0660	+ 8
74	178.0	8.61	1.30	2.80	0.164	+10
58	180.0	8.15	0.80	1.20	0.0923	-13
63	183.0	5.38	0.85	1.30	0.145	-27
69	183.0	12.2	1.00	1.70	0.0985	- 4
57	184.0	10.2	0.63	1.00	0.0537	0
61	186.0	21.0	1.25	1.00	0.0688	- 1
24	221.0	7.05	0.80	1.30	0.0868	+ 9
1	352.0	18.1	0.95	1.50	0.0616	+20

Table 3--Distribution of error

Error	Watersheds	
	Number	Per cent total
pct		
0 - 5	18	35
0 - 10	25	49
0 - 15	32	63
0 - 20	39	76
0 - 25	41	80
0 - 30	46	90
0 - 35	49	96
0 - 37	50	98
0 - 67	51	100

To test the reliability of these long-term values of $(p^{0.929}\ S^{0.449})$ all watersheds with periods of runoff records of 20 or more years were selected. Peak-rate probability curves were computed for each watershed and the peak rate, q, for a ten-year recurrence interval was compared with the theoretical value q_c determined by substituting values for A, T, and long-term values of $(p^{0.929}\ S^{0.449})$ in the regression equation. The results of this test are shown in Table 4.

Frequency factors--The relationships expressed by the regression equation are between rainfall and topographic factors and the peak rate of runoff for a ten-year recurrence interval. Since many structures are designed for peak rates corresponding to recurrence intervals greater than ten years, an investigation was made to determine the relationship between peak rates for a ten-year recurrence interval and those for 25- and 50-year intervals. For each of the 51 watersheds, the ratios of the 25- and 50-year peaks to the ten-year peak were determined from the peak-rate probability curves. The ratios of the 50-year to 10-year peak were found to vary from 1.24 to 1.54. When this ratio for each watershed was plotted on a map, it was found that they had an areal significance; that is, nearly all of the watersheds having low ratios were located in the northerly portion of the area and those having high ratios were located in the southerly portion. The area was accordingly divided into two zones (Fig. 1). The boundary between zones was made almost identical with those between various Soil Conservation Service problem sub-areas.

Table 4--Comparison of q and q_c for various watersheds

Watershed number	Area	Record	q_c	q	$\frac{q_c - q}{q_c}$
	1000 ac	yr	cfs/ac	cfs/ac	pct
57	184	20	0.052	0.050	+ 4
25	55	21	0.077	0.081	- 4
63	183	23	0.114	0.119	- 4
22	116	27	0.067	0.079	-16
19	120	29	0.079	0.075	+ 5
21	177	32	0.068	0.062	+ 9

The average ratio of 25-year to 10-year peaks for the 27 watersheds in Zone 1 was 1.20 and that for the 50-year to 10-year peak was 1.34. These averages for the 24 watersheds in Zone 2 were 1.26 and 1.46, respectively. For both zones the standard deviation for the 50-year to 10-year ratio was ±0.04. In terms of per cent difference in 50-year peak rates of runoff, the standard deviation for Zone 1 was ±3.0 pct and that for Zone 2 was ±2.7 pct.

It was at first thought that the difference in the slope of the peak-rate probability curves, as measured by the ratio of the 50-year peak to the 10-year peak, was due to differences in vegetal cover between the various watersheds. A survey, however, showed that the per cent of the watershed in cropland, pasture, and woodland had no significant effect on the magnitude of the 50-year to 10-year ratio.

Because high values of the S-ratio and the 50-year to 10-year ratio are both found in the southerly portion of the area, the possibility of a relationship existing between the two ratios was next investigated. For each watershed, the ratio of the 50-year to 10-year peak was plotted against the S-ratio. In spite of a considerable scatter of the plotted points, a sufficiently definite trend was discernible to indicate that the slope of the peak-rate probability curve depended, to some extent, on the magnitude of the S-ratio.

Although no data are available on which to base definite conclusions, it is thought probable that the slope of the peak-rate probability curve is also dependent on the hydraulic properties of the soil. Some soils have greater water-holding capacity than others due either to greater depth, greater porosity, or both. Also, some soils have higher infiltration and percolation rates which result in a nearly saturated condition being reached in a shorter period of time.

If the differences found between the slopes of the peak-rate probability curves are indicative of physiographic and rainfall differences, then it might be suspected that some of the variation in peak rates unexplained by the regression equation could be ascribed to these differences. An investigation indicated, however, that within the range of the experimental data the effect of these differences on the magnitude of the ten-year peaks would probably be small. For this reason and because of the limited data now available, it was thought that the computation of a separate correlation for each zone was not justified.

Conclusion--The reliability of peak-rate estimates based on short-term runoff records can be greatly increased by the introduction of carefully selected rainfall and topographic factors as independent variables in a multiple correlation.

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PUMPING FROM WELLS ON THE FLOOR OF THE SEVIER DESERT, UTAH

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Abstract--Data collected at the Topaz Relocation Center provide an excellent record of the development and subsequent disappearance of a cone of depression caused by pumping. This Center occupied temporarily an area of natural ground-water discharge on the floor of the Sevier Desert in west-central Utah. Water for a population of 6500 was pumped from artesian wells which tapped aquifers of sand. Overlying these sand beds are lake-bed sediments too impermeable to yield water to wells, but apparently permeable enough to permit slow upward movement of water from the artesian aquifers. The water table is near the surface, and there is natural discharge by evapotranspiration, accumulation of "alkali" in the soil, and a need for drainage of irrigated lands. The wells were abandoned when the Relocation Center was closed, apparently because these handicaps were so great that the ground water could not be used profitably for irrigation.

Introduction

Water shortage is customary in the Southwest, so much so that it is fundamental in the philosophy of most of the inhabitants of the region. Indeed, some of those who are fortunate enough to have an abundance of water use all of it and still plead shortage, lest their water supplies be eyed covetously by less fortunate neighbors. Yet a significant proportion of the region's limited water resources is dissipated by natural discharge; by evaporation from saline lakes and alkali flats, and by transpiration of vegetation that has little or no economic value. The quantity of natural discharge, if it could be salvaged, would be enough to supply scores of cities of a million inhabitants each, or to irrigate several million acres of desert land [ROBINSON, 1949]. A large proportion of this natural discharge is from the ground-water reservoirs of the region.

Many difficulties are likely to greet efforts to salvage and use beneficially the ground water now lost by natural discharge. In some areas, ground water is intercepted along its route to areas of natural discharge, and pumped from wells for irrigation. It may take years of pumping, however, to cause any appreciable reduction in the rate of natural discharge, and in the meantime the pumping is likely to remove large quantities of water from permanent storage in the ground-water reservoir. The ground-water development in the southern part of Escalante Valley, Utah, is of this type, as shown in a recent report [FIX and Others, 1951].

An alternative is to develop the water within or adjacent to the area of natural discharge. The history of the development and use of water at the Topaz Relocation Center in central Utah is considered to be of significance throughout the southwestern United States because it represents an attempt tc salvage water from an area of natural ground-water discharge, in a closed basin that is more or less representative of many valleys of the region.

Environment of the Topaz Relocation Center

The Sevier Desert embraces an area of about 2500 sq mi in west-central Utah (Fig. 1). Most of it is a fairly level plain, merging into alluvial slopes along its borders. Although this plain is more than 4500 ft above sea level, it constitutes the lowest land in a broad region, for it lies among mountain ranges that rise several thousand feet higher. The lowest part of the Sevier Desert is occupied by Sevier Lake.

The climate justifies the term "desert," for the annual precipitation is less than ten inches in most years: at the town of Deseret it has ranged from 3.1 to 11.3 inches in the past 58 years, with an annual average of 7.6. Commonly less than 1 1/2 inches of rain falls during the summer (June, July, and August), and most of the annual precipitation falls during five months (February-May, and October). During the frost-free growing season, which averages about 120 days in length, irrigation is essential for all cultivated crops.

Most of the mountains bordering the Sevier Desert are low ranges which probably receive little more precipitation than does the valley plain. Small perennial streams rise in the higher

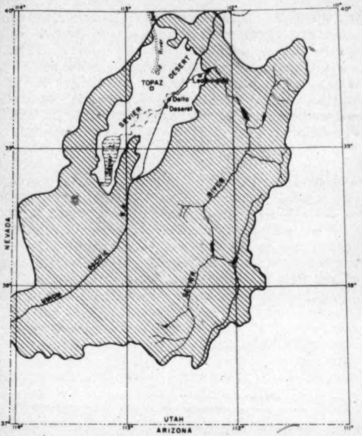

Fig. 1--Map of Sevier River drainage basin in southwest Utah, showing location of Topaz Relocation Center

ranges, but they are diverted and used for irrigation long before they reach the desert plain, and the lower parts of their channels are dry practically all the time.

The principal source of water for the Sevier Desert is the Sevier River, which heads in the high plateaus of southern Utah, flows northward more than 150 miles, turns westward through the Canyon Range, and then flows out upon the Sevier Desert at the town of Leamington. The drainage basin above Leamington has an area of about 6200 sq mi. The water of the Sevier River, fully regulated by the Otter Creek, Piute, and Sevier Bridge Reservoirs, irrigates about 40,000 acres of the Sevier Desert, in addition to serving many other agricultural areas along its course. Half a dozen towns are situated in the irrigated area of the Sevier Desert, of which the largest is Delta, with a population of about 1300 in 1940, which increased to 1700 in 1950. The desert has a total population of about 5000.

In 1942 the Federal War Relocation Authority selected 28 sq mi in the central part of the Sevier Desert, set up the Topaz Relocation Center, and transferred to it some 6500 people of Japanese ancestry who had lived in the Pacific Coast States. Prior to the establishment of the Relocation Center, the population of the area was very small, but the inhabitants had rights to Sevier River water, which they used for irrigation. For the Center, facilities such as barracks, schools, stores, and a hospital were constructed on one square mile of land to accommodate 7000 persons. The rest of the land was used for raising hogs, cattle, chickens, hay, and grain in a combination activity-and-food program for the relocated people. The Sevier River provided water for irrigation, because water rights were included in the purchase of the land. Wells were drilled to provide water for domestic use.

The population at the Center was estimated to have been about 6500 from September, 1942, to June, 1944, and was about 6000 in the following eight months; by August, 1945, it had dwindled to 5700. Evacuation was rapid and thorough in the following three months. By December, 1945, only caretakers remained, and the operations at the Center thereafter were limited to the disposal of the Government property.

Hydrologic history of the Sevier Desert

Under present climatic conditions the Sevier Lake drainage basin is a closed basin, and the precipitation that falls upon it must eventually be returned to the atmosphere within the basin. The surface water as well as the ground water in the drainage basin moves toward the lowest area, which is the Sevier Desert. It comes from tributaries that flow only as a result of heavy rainfall or snow melt; it comes as underflow in canyons that hardly ever carry enough water to produce a surface stream; it comes as ground water from infiltration through permeable materials in the valley; but chiefly it comes from the Sevier River. Much of this water is caught up by evaporation and transpiration en route, but a large amount remains to be disposed of in the Sevier Desert.

The natural discharge from the Sevier Desert fluctuates according to the total inflow. Beneath the desert floor the earth materials are saturated to within a few feet of the surface; ground water is shallow enough in broad areas to be subject to evaporation, and in larger areas it is within reach of plant roots. In a series of wet years producing greater-than-average inflow to the area, the water table rises and the rates of evapotranspiration increase. If inflow is great enough, water continues to accumulate until it stands above the land surface. Sevier Lake and other intermittent lakes expand in the lower parts of the basin, until evaporation from their surfaces is sufficient to reestablish the balance between inflow and discharge. Dry cycles and decreasing inflow reverse these processes: Sevier Lake contracts and may dry up, and the water table drops until natural discharge is reduced to equivalence with the inflow.

Although the Sevier Desert readily dissipates the water that comes to it, it has no means of disposing of the mineral matter dissolved in that water. Those salts remain on the surface, or in the soil, or in the shallow ground water. When Sevier Lake contracts it leaves a white salt flat, unsuitable for any use. Most of the desert has soils that are too saline for agricultural use. The Sevier Desert is afflicted, not by a shortage of water, but by a shortage of usable water. It has too much water of inferior quality, and a surfeit of soluble salts left by the water as it returns to the atmosphere. The residents of the desert know this. Agriculture is successful only in carefully selected areas, and many of those areas require drainage to hold the water table down to satisfactory depth.

The present arid climate, with minor variations, has persisted for several thousand years. But before that time, the climate was colder or more humid, or both. At the time of Pleistocene Lake Bonneville, water accumulated in the Sevier Desert and in many other closed basins in Utah and Nevada, overflowed into other basins, and for a while formed a lake as large as Lake Michigan. At its higher stages Lake Bonneville discharged into the Snake River through an outlet in Idaho. The Sevier River was one of the large contributors to Lake Bonneville, and it built a huge delta at the mouth of its canyon at Leamington. That delta is a prominent feature of the Sevier Desert today. It is composed chiefly of gravel and sand near Leamington and of finer sediments at greater distances from the edge of the lake. Its outer edge is near the town of Delta, and its upper layers form the soils of much of the irrigated area. The rest of the Sevier Desert was once the bed of the lake, where lacustrine clays accumulated to depths as great as 100 ft.

During the late stages of Lake Bonneville there was outflow from the Sevier Lake basin northward to the Great Salt Lake basin. The old river bed is visible today, a broad shallow channel about two miles west of the Topaz Relocation Center. Outflow may have occurred similarly at various times in the geologic past, and during those times the soluble salts carried by the water would also be discharged northward rather than remain in the basin as they do today. Fresh water in the sediments of probable Pleistocene age suggests that there was outflow from the basin during most, if not all, of the Pleistocene. On the other hand, saline water in the deeper pre-Pleistocene beds indicates that those sediments may have accumulated in a closed basin under arid conditions similar to the present.

Adjacent to the Sevier Lake basin there are several basins which today have interior drainage, but which have discharged into the Sevier Lake basin for extended periods in the geologic past. Escalante Valley is the largest of these. These basins have contributed water, soluble salts, and sediments to the Sevier Lake basin.

Throughout Tertiary and Quaternary time, the geologic history of the region has been one of erosion of the mountain ranges and transportation of sediment to the lowlands, where it has been deposited to form the broad valley plains that characterize the region today. Under the Sevier Desert those sediments are known, from well drilling, to be more than a thousand feet thick, and they may be considerably thicker. Thus water has played an outstanding role in the development of the Sevier Desert and other valley plains in the region.

Ground water at the Relocation Center

The aquifers--Information concerning the sediments underlying the Relocation Center is obtained chiefly from the three deep wells that were drilled to supply the Topaz community. These wells were drilled along a north-south line just east of the community, and are 1000 to 1200 ft apart. The central well was drilled to a depth of 996 ft, after which the north well was drilled to 855 ft and the south well to 658 ft. The quantity and quality of water in individual aquifers were not tested during the drilling. The drillers' logs of the three wells agree in principle but not in detail, perhaps because of discontinuities of individual beds, and perhaps because of differences in the drillers' identification of the sediments brought up in the mud during the rotary drilling. The composite log of Table 1 is an interpretation of the data contained in the three well logs.

Many wells had been drilled for domestic use in the vicinity prior to the establishment of the Center. So far as known, these wells are 100 to 300 ft deep and none is deep enough to reach the deep salt-water-bearing beds. The clay encountered in the upper 100 ft of each well was deposited on the bottom of Lake Bonneville while the Sevier River was building its huge delta farther

Table 1--Interpreted composite log of Topaz supply wells

Material	Thickness	Depth
	ft	ft
Lake Bonneville group of Pleistocene and Recent age		
Clay, lacustrine	100	100
Pre-Lake Bonneville deposits, probably of Pleistocene age		
Clay, interbedded with water-bearing sand, individual wells show two to eight sand beds, each not more than ten feet thick, and totaling not more than 52 ft	215	315
Clay, with thin discontinuous lenses of sand at 400-420 ft and 590-615 ft	300	615
Clay	175	790
Beds, probably of pre-Pleistocene age		
Coarse sand, pebbles of volcanic rock	20	810
Clay, with discontinuous lenses of sand at 820-835 ft	57	867
Gravel and sand, bearing saline water	129	996

east. In a well drilled four miles nortneast of the Topaz supply wells, clay is dominant in the upper 120 ft, but four beds of sand were also encountered, each two to four feet thick. Still farther east, toward the axis of river deposition, the clay in the beds of the Lake Bonneville group is interbedded with an increasing proportion of sand and gravel.

Deep artesian water--Only the two deepest wells at Topaz reach the pre-Pleistocene aquifers. Those aquifers are productive, but the water was too highly mineralized for use by the Relocation Center. After this became apparent, efforts were made to shut out the deep water in both wells, but subsequent records indicate that some inferior water rose through the plugs and contaminated the shallower water.

Developed artesian water--Practically all the usable ground water that has been developed in the Topaz area comes from the pre-Lake Bonneville deposits of probable Pleistocene age. The good water obtained by the Topaz supply wells comes from these beds at depths of 100 to 615 ft. The other wells in the vicinity evidently tap these same beds. The water is confined under artesian pressure and may flow at the land surface, but the yield of flowing wells is generally less than five gallons per minute.

It is characteristic of the valley fill of Utah's intermontane valleys that the deep aquifers naturally have a higher piezometric surface than do shallow aquifers. This may be true also in the Topaz area, but existing wells are too few in number, and too little is known about their depths, to define the piezometric surfaces of individual aquifers. Available data indicate that there are differences of artesian pressure in nearby wells of different depths, but that these differences are probably not greater than a foot or two.

The piezometric surface shown in Figure 2 is based on measurements of shut-in pressure in 14 wells during August, 1942, prior to pumping from the Topaz supply wells. The depths of most of those wells are unknown. This piezometric surface has a general westward gradient of about five feet per mile, equivalent to that of the land surface. Thus this confined water moves into the Topaz area from the general direction of the delta of the Sevier River. The contours also suggest that the water moves westward through the area and beyond, but, as pointed out below, it may be dissipated in part by upward movement rather than westward movement.

Unconfined water--The unconfined water is that which occurs within the beds of the Lake Bonneville group. These beds are saturated to within a few feet of the land surface, but are generally so fine-textured that they yield very small quantities to wells. A few wells, dug to thin sand lenses at shallow depths, furnish water in sufficient quantity for domestic use, but the water is generally highly mineralized. Thus the unconfined water is practically valueless in the Topaz area.

The unconfined water is a serious handicap in most of the Sevier Desert. In large areas alkali has accumulated in the soil as the water evaporated, so that those lands are worthless for agriculture. Irrigation with Sevier River water has raised the water table under thousands of

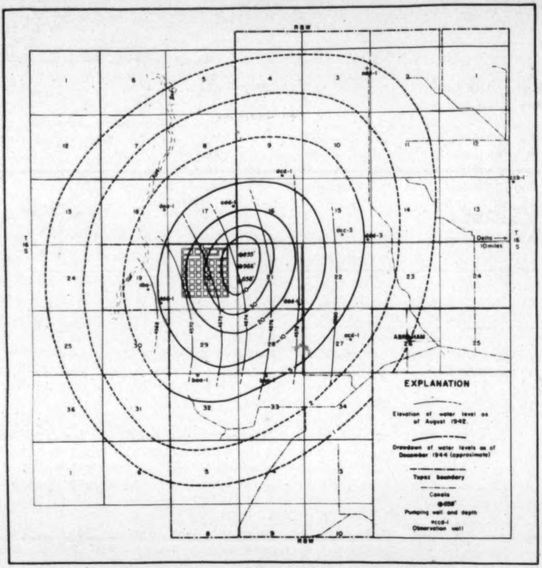
R8W
T
16
S
Delta
10 miles
ABRAHAM
EXPLANATION
Elevation of water level as of August 1942.
Drawdown of water levels as of December 1944 (approximate)
Topaz boundary
Canals
Pumping well and depth
Observation well

Fig. 2--Map of Topaz area, Utah, showing piezometric surface in August, 1942, and composite cone of depression in December, 1944

acres of land, with resulting increase of alkali in the soils of many irrigated areas. Alkali is excessive in extensive areas in the eastern part of the Relocation Center area, where irrigation has been practiced for many years. Drainage ditches have been required in most of the irrigated area to hold the water table at sufficient depth for farming and to prevent man-made increases of alkali in the soil. In order to farm the land acquired for the Relocation Center, new drainage ditches were dug and old ones deepened.

The western part of the Relocation Center includes extensive areas that have never been irrigated. There too the concentration of alkali in the soil is high, or even excessive in many places. Locally the upper foot or two of soil contains concentrations of water-soluble salts in lenses parallel to the bedding planes. In these areas the alkali is evidence of natural discharge of water that is not related to irrigation.

The water table is more or less parallel with the land surface in the Topaz area, as shown by the fairly uniform depth at which it is encountered in pits and ditches. Thus the water table has a slight westward gradient. The sources of the water that is discharged by evapotranspiration throughout the area may be many. Undoubtedly most of the desert precipitation returns to the atmosphere without penetrating more than a few inches below the land surface, but melting of snow may recharge the shallow ground water as indicated by rises of water level in dug pits in the early months of some years. Surface water applied for irrigation has caused the water table to rise in irrigated areas, and some of that water may well move westward under the unirrigated areas of the Relocation Center; the lake beds are predominantly clay, however, and lateral movement of water in them must be very slow.

A large proportion of the water in the beds of the Lake Bonneville group may come from the underlying artesian aquifers. In Cache Valley in northern Utah, ISRAELSEN and McLAUGHLIN

[1932 and 1935] have shown that there is upward movement of water from artesian aquifers through overlying beds of the Lake Bonneville group, and there is increasing evidence that such movement is common in many other valleys once inundated by Lake Bonneville.

Trends of water-level fluctuations in wells in the Sevier Desert--Water levels or artesian pressures are measured annually or oftener in 12 to 15 wells in the Sevier Desert, and the measurements are published in water-supply papers of the U. S. Geological Survey. A severe drought cycle ended in 1935 and in the succeeding 15 years the water levels in observation wells rose more than a foot, on the average. This rise correlates with a rising trend in precipitation, which increased from an annual average of 5.2 inches in the five years 1931-35 to an average of 7.9 inches in the years 1943-47. It correlates also with a rising trend in runoff of the Sevier River: at the gaging station near Juab, Utah (below the Sevier Bridge Reservoir), the runoff totaled 456,000 ac ft in the five years 1932-36, and increased to a total of 860,000 ac ft in 1942-46.

The fluctuations of water levels in wells generally are of small magnitude, rarely more than a foot in a year. These fluctuations do not correlate in detail with fluctuations in precipitation or runoff. Thus the water levels in most wells did not rise markedly in the three years out of the 15 when precipitation at Deseret exceeded ten inches (1936, 1941, and 1946). Nor was there any very general response to high runoff in the Sevier River, approximating 200,000 ac ft in 1942, 1946, and 1948.

Effects of pumping the Topaz supply wells

History of pumping--Pumping from the three deep wells at Topaz began in September, 1942, and continued for 39 months through November, 1945. In 12-hour tests the wells produced respectively 720, 430, and 525 gal/min. The central and deepest well, although it had the largest pump, was used only during periods of peak consumption because of the poor quality of its water, and it was shut down permanently in July, 1945. In September, 1942, the non-pumping water levels in the wells were slightly above the land surface; by December, 1944, when the rate of pumping reached its maximum, they had declined as much as 22 ft. The drawdown ranged from 28 to 35 ft, and the pumping lift reached a maximum of nearly 60 ft in December, 1944. Tests showed the specific capacity of each of the three wells to be 27 to 30 gal/min per foot of drawdown.

Monthly pumpage from the wells increased from about 0.7 million gallons per day (mgd) in September, 1942, to 1.0 mgd in the following summer. From October, 1943, to July, 1944, inclusive, the pumping was at a rather constant rate of about 0.8 mgd. In the following three months the draft exceeded 0.9 mgd, and the maximum monthly pumpage in the 40-month period, about 1.2 mgd, occurred in December, 1944, and January, 1945, because of leakage from the distribution mains. Monthly pumpage, in acre feet, is shown graphically on Figure 3. The total pumpage from the wells is estimated to have been about 2900 ac ft.

Interference with other wells--Pumping from the Topaz supply wells interfered appreciably with the flow from the several small-diameter artesian wells that dot the area of the Relocation Center. In large part, the effect was related to the distance from the pumped wells. A well 60 ft from one of the pumped wells stopped flowing within three hours after the pump was started. Some wells within a mile of the pumped wells stopped flowing within a month, and all had ceased flowing after four months of pumping. The effect upon more distant wells was more gradual, and less pronounced: some wells between one and two miles from the pumped wells continued flowing for nearly a year after pumping began, but all had ceased flowing by December, 1944. The hydrographs of Figure 3 show the effects of pumping upon water levels in nine wells that are within 10,000 ft of the pumped wells.

The declines in water level in these artesian wells are not directly proportional to their distances from the pumped wells. The water level in a well 8000 ft northeast declined appreciably less than that in another well 2000 ft farther northeast, and it is probable that those wells are of different depths and reach different aquifers. In a well 5000 ft southeast of the pumped wells, the decline was at a lesser rate than in a well 6700 ft northwest indicating variations, either laterally or vertically, in the aquifers tapped by the two wells.

Development and disappearance of the cone of depression--The small-diameter artesian wells are driven or jetted to various depths, probably within the range 100 to 300 ft below the surface. Each obtains water from the lower open end of its casing, and therefore from only one point in a single aquifer. As a group, however, they obtain water from various depths, and therefore from many individual sand beds.

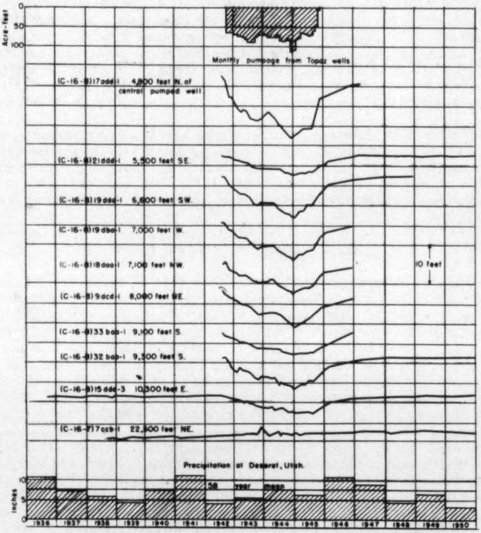

Fig. 3--Hydrographs of ten wells in the Topaz area, Utah, showing fluctuations of water levels and related data, 1936-1950

The casings of the three pumped wells are perforated below the depth of 130 ft, and each casing is surrounded by a gravel envelope averaging seven inches in thickness. Thus these wells can draw from any bed below the depth of 130 ft that will yield water. They draw water from all aquifers in the range of depths penetrated by the small artesian wells, except those that are less than 130 ft deep. Pumping, then, would cause interference in adjacent wells reaching the same aquifer. But interference was measurable in all artesian wells, regardless of depth, within a wide area surrounding the pumped wells; and it appears either that the several aquifers are fairly continuous, or, if discontinuous, they are sufficiently interconnected that the effect of pumping is distributed throughout the water-bearing beds of probable Pleistocene age. Hundreds of observation wells would be needed to chart the effects of pumping upon the piezometric surfaces of the individual aquifers. The records obtained are sufficient only to define roughly a composite cone of depression for the group of aquifers that occur in the Pleistocene sediments.

The cessation of flow and the declining water levels in artesian wells are evidences of the development of that cone of depression. This cone in the Topaz area deepened and expanded while the rate of pumping was held constant, and its size increased more rapidly when the pumping rate increased. Figure 2 shows the form of the cone of depression during its maximum development, in December, 1944. The observation wells provide relatively few points for the determination of that form; elsewhere the form is based on the theoretical straight-line relationships between the logs of the drawdowns in the observation wells and their radial distances from the pumped wells. As shown in Figure 2, the area in which artesian pressures were lowered more than one foot was oval-shaped, with a northeast-southwest axis of about six miles, and a northwest-southeast axis of about five miles. The piezometric surface was lowered more than 30 ft in an area of one square mile, and more than five feet in an area of nine square miles.

Conversely, the cone of depression diminished in volume during 1945 as the rate of pumping decreased. After pumping ceased, in December, 1945, the water levels in artesian wells rose at rates more or less comparable to the declines in the early months of pumping, and erstwhile flowing wells resumed their flow. By December, 1947, the water levels in all wells were approximately as high as they were before pumping began, and the cone of depression had disappeared.

Coefficients of transmissibility and storage--COOPER and JACOB [1946] have developed a graphical method for determination of the coefficients of transmissibility T and storage S of water in artesian aquifers from which a well is discharging at changing rates, based upon measurements of the drawdown s in an observation well at distance r from the discharging well. The straight-line plot for each observation well is based upon the equation

$$(s/Q)^n = (2.303/4\pi T)\,[\log_{10}(r^2/t)^n - \log_{10}(2.25\,T/S)]\ldots\ldots\ldots\ldots(1)$$

in which $(s/Q)^n$ is the specific drawdown, or drawdown per unit of discharge; and r_n is the weighted mean logarithmic distance corresponding to the distance at which a single well discharging at rate Qn would produce the drawdown s^n at the elapsed time t^n after discharge began. The distance r_n at a given time is computed by multiplying each increment of discharge that occurred before the given time by the logarithm of the distance to the discharging well, summing the products algebraically, dividing the sum of the products by the algebraic sum of the increments of discharge, and extracting the antilogarithm of the quotient.

The coefficient of transmissibility T is determined by the slope of the straight-line plot, according to the equation

$$T = -2.303/[4\pi\,\Delta(s/Q)^n] = -1/5.46\Delta(s/Q)^n\ldots\ldots\ldots\ldots(2)$$

and the coefficient of storage S is determined as

$$S = 2.25\,T/\overline{(r^2/t)}_o\ldots\ldots\ldots\ldots(3)$$

where $(r^2/t)_o$ is the value of $(r^2/t)_n$ at the intercept.

The data collected at Topaz are inadequate for more than a rough approximation of these coefficients by this method. The three wells were pumped intermittently as necessary to maintain storage in the supply tanks, with least pumpage from the central well because of the inferior quality of the water. Neither the discharge from individual wells nor the draft from the supply tanks was metered. Engineers at the Center computed the approximate monthly draft on the basis of hours of pump operation, short tests to determine well discharge, and per-capita consumption during March and April, 1945. According to these computations, the average monthly discharge was fairly constant in periods ranging from two to ten months in length, although the discharge fluctuated markedly from hour to hour and from day to day. The periods of constant rate of monthly discharge are listed in Table 2.

Table 2--Periods of pumping from Topaz wells

Period	Length of period	Average discharge
	day	mgd
Oct. 1, 1942 to Jan. 1, 1943	92	0.74
Jan. 1, 1943 to July 1, 1943	181	0.85
July 1, 1943 to Oct. 1, 1943	92	0.98
Oct. 1, 1943 to Aug. 1, 1944	305	0.83
Aug. 1, 1944 to Dec. 1, 1944	122	0.96
Dec. 1, 1944 to Feb. 1, 1945	62	1.20
Feb. 1, 1945 to Apr. 1, 1945	59	0.88

The drawdown s during each of these periods was computed from the records of water levels in each of nine observation wells. The computations of r_n are based upon the distance between the central pumped well and the individual observation wells; thus these computations assume that all the discharge was from one point rather than from three.

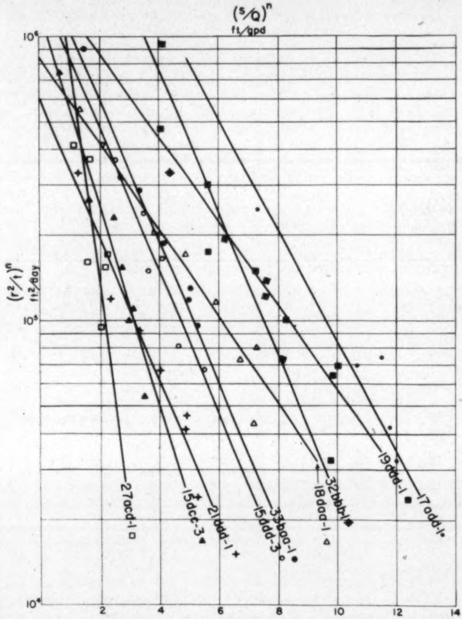

Fig. 4--Generalized composite drawdown graphs for nine wells in the Topaz area, Utah, October, 1942, to March, 1945

The resulting straight-line plots are presented in Figure 4. The graphs for four of the wells are practically parallel, and indicate very nearly the same coefficient of transmissibility. In the nine wells the coefficient of transmissibility ranged from 27,000 to 142,000 gallons per day per foot with an average of 53,700, as shown in Table 3. The coefficient of storage S ranged from 0.0039 to 0.0225, with an average of 0.0097 for the nine wells.

By planimetry of the areas encompassed by the contours in Figure 2, it is estimated that the volume of the cone of depression at its maximum development was of the order of 120,000 ac ft. The quantity of water released from artesian storage in the development of this cone would therefore be of the order of 1200 ac ft. The rest of the 2900 ac ft pumped from the Topaz wells was evidently intercepted by the supply wells along its path of natural westward movement.

Possible effect upon unconfined water--Most of the water pumped by the Topaz wells appears to have been replaced by movement in the aquifers within two years after cessation of pumping, and therefore the natural cycle of movement and natural discharge of ground water took up where it had left off prior to the pumping. But during the existence of the Relocation Center the withdrawal of this water must have resulted in a corresponding diminution of natural discharge somewhere. Because the Topaz area is itself an area of natural ground-water discharge, it is logical to look there first.

The natural discharge at Topaz could have been reduced by the pumping only if there was upward movement of water from the artesian aquifers under natural conditions. Such upward movement would be reduced when artesian pressure is lowered, and the eventual result might be a

Table 3--Coefficients of transmissibility and storage

Well[a]	Depth of well	Coefficient of transmissibility, T[b]	Coefficient of storage, S[c]	Record
	ft	gpd/ft		
(C-16-8) 32baa-1	104	46,700	0.0190	Good
(C-16-8) 21ddd-1	125	45,800	0.0225	Good
(C-16-8) 19ddd-1	128	27,100	0.0049	Good
(C-16-8) 17add-1	189	36,100	0.0039	Poor
(C-16-8) 15ddd-3	190	46,700	0.0094	Good
(C-16-8) 19daa-1	?	27,800	0.0098	Good
(C-16-8) 27acd-1	?	142,000	0.0089	Fair
(C-16-8) 33baa-1	?	46,700	0.0076	Good
(C-16-8) 15dcc-3	?	64,300	0.0155	Good
Average		53,700	0.00973	

[a] The well number is based upon its location by land subdivision. The designation (C-16-8) indicates that all these wells are in T 16 S, R 8 W, S. L. B. and M. The number following the parentheses designates the section, and the letters a, b, c, and d refer respectively to the NE, NW, SW, and SE quarters of the section, quarter-section, and sixteenth section, in that order.

[b] Coefficient of transmissibility is defined as the amount of water, in gallons a day, transmitted under prevailing conditions through each vertical strip of the aquifer one foot wide, having a height equal to the saturated thickness of the aquifer, under a unit gradient.

[c] Coefficient of storage is defined as the volume of water released from storage in each vertical column of the aquifer having a base one foot square, when the water table or other piezometric surface falls one foot.

lowering of the water table in the beds of Lake Bonneville, and therefore a decrease in rate of evapotranspiration. Unfortunately there are no records of water-table fluctuations in the vicinity of the pumped wells to show whether this has occurred. The war-emergency ground-water studies in the Topaz area were concerned only with the aquifers that provided water for the Relocation Center, and the shallow mineralized water did not enter into that picture.

There is some indirect evidence that the water table may have been affected by the pumping. Three of the observation wells consist of pits dug below water table, with pipes driven into the bottom to tap artesian aquifers; thus the water level in the pit is a compromise between the water table of the unconfined water and the piezometric surface of the confined water. The fluctuations in these wells were similar to those in wells which tapped only the confined water. Furthermore, the coefficients of storage derived in Table 3 appear to be higher than usual for true artesian conditions, and may be an indication of drainage into the aquifer from the fine-textured materials of the Lake Bonneville group.

Deterioration in quality of water--The flowing wells in the Topaz area have long been used for domestic purposes and stock watering. Analysis of a sample from one of them shows the water to be a sodium bicarbonate water having about 400 parts per million (ppm) of dissolved solids. The shallowest pumped well at Topaz, which obtained water from depths of 130 to 640 ft, yielded water of very similar quality. This water is satisfactory for most rural uses, although it is so soft that it caused pitting of the boilers in the heating plant at the Relocation Center. The quality of water from this supply well did not change materially throughout the three years of pumping.

The 855-foot well at Topaz went through these aquifers of usable water, and on into deeper beds bearing saline water. It was subsequently plugged at a depth of 640 ft, and the perforations and gravel wall extend down only to a depth of 632 ft. The well upon completion yielded a sodium bicarbonate water comparable to that in the wells mentioned above, and had 440 ppm of dissolved matter. However, the quality deteriorated gradually but progressively as the well was pumped. A sample of water taken in September, 1945, contained 931 ppm of dissolved matter, chiefly sodium chloride. A year after pumping ceased the water flowing from the well was again similar to that from the shallow flowing wells. Evidently the temporary deterioration resulted from rising of deep saline waters under conditions of long-continued heavy draft.

The saline waters in the deepest (996-ft) well were never sealed off satisfactorily. After plugging attempts in 1942, there was a hopeful sign when a sample from the 600-ft depth showed only 659 ppm of dissolved solids. But samples collected each year thereafter showed 1400 ppm or more. A sample of the water flowing from the well in February, 1949, more than three years after cessation of pumping, contained nearly 1900 ppm of mineral matter.

Some deterioration in quality of the water is possible with long-continued pumping, because of gradual drainage of mineralized water from clay and other materials of very fine texture. There is no indication that such deterioration occurred during the pumping at Topaz unless a gradual increase in sodium and potassium bicarbonate in the water from the shallowest pumped well can be considered such an indication. It has been noted that there was no increase in dissolved solids in the water from that well.

Conclusions

The objective of development of ground water at the Topaz Relocation Center was to provide water for domestic use for a population of 6000 or more. The wells met this objective successfully, and they would have been even more successful if the aquifers had been tested as drilling progressed, so that the troubles with deep saline water could have been avoided.

With respect to perennial yield of water the ground-water development at Topaz was also successful. The two good wells each proved themselves capable of a sustained yield of about 1000 ac ft a year, or 900,000 gallons per day.

The economic feasibility of agricultural development within an area of natural ground-water discharge is more dubious. The two good wells, if pumped at the same rates as for the Relocation Center, would provide enough water during the growing season to irrigate about 120 acres. Or if the annual pumpage at the Center were concentrated in a four-month growing season, 360 acres could be irrigated, but pumping lifts must then be considerably greater. Whether such irrigation would be economically feasible would depend upon the capabilities of the prevailingly poor soils to produce crops that would pay for the cost of pumping and the cost of any drainage that might be necessary.

The answer to these questions, so far as Topaz is concerned, would seem to be contained in the postwar history of the Relocation Center area, when all the Government property was declared surplus. Evidently no one could see any way to use the water-supply system profitably, although that system could have been purchased for a small fraction of its cost. The pumps, tanks, distribution mains, and other equipment were sold as separate parcels, and removed from the area.

Acknowledgments--This article is based largely upon data collected during studies by the U. S. Geological Survey of ground-water developments at World War II emergency installations, of which the Topaz Relocation Center was one. The authors are indebted to P. E. Dennis of Texas Technical College, who was in charge of this program in Utah during World War II, and to C. E. Jacob of the University of Utah for valuable suggestions and criticism in the preparation of this article. The field studies were done in cooperation with the War Relocation Authority, and many of the basic data were collected by Henry Watson and Wallace Crane, engineers for that agency. Illustrations were prepared by Glenn Butler.

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CHARACTERISTICS OF TIPPING-BUCKET DEVICES

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Abstract--The results of tests and a description of the behavior of a tipping-bucket gage for use in flow measurements are given. Procedures for the use of these devices to obtain as reliable flow data as possible are indicated. It is concluded that, because of the large head room required and the low capacity in addition to the poor hydraulic characteristics, this type of instrument is unsuitable for adoption for general use in the measurement of soil and water runoff from experimental areas.

Definitions and symbols--The more important definitions have been collected below to facilitate reference. They are followed by a table of symbols subsequently employed.

Flow: The rate of flow of the gaged stream; herein expressed in cubic feet per second, abbreviated cfs (1 cfs = 448.8 gal/min)

Delivery: The volume of liquid passing the gage for each tip of the bucket; here measured in cubic feet

Zero-flow delivery: The limiting delivery as the flow approaches zero. This is the minimum volume delivered by the bucket. It is determined experimentally by adding liquid drop by drop at the time of incipient tipping, thus preventing any effects of an entering jet.

Rate of tipping: The number of times the bucket tips per unit of time; here expressed in tips per minute

Angle of tip: The angle between the vertical and the central partition when the bucket is at rest

Counterweight: A weight fastened to the lower end of the bucket frame for some of the tests. The effect of a counterweight is to lower the center of gravity of the bucket toward the fulcrum and thus reduce both the moment and the delivery of the bucket.

Rating curve: A curve showing the relation between the rate of tipping of the bucket and the flow in the gaged stream.

Q	Rate of flow, cfs
V	Delivery of bucket in general, cubic feet
V_o	Delivery of bucket at zero flow, cubic feet
α	(Alpha) angle of tip, degrees
W_c	Counterweight, pounds
M	Moment in general (moment = force × length of lever arm)
M_b	Moment of the bucket and its appendages about the knife-edge fulcrum
M_1	Moment of the liquid contents of the bucket about the knife-edge fulcrum

Other symbols will be defined where used.

Introduction--Many devices have been invented for the measurement of the total quantities and the rates of flow of small liquid streams that consist of a pair of compartments that are alternately filled by the stream and that tip from one side to the other about a fulcrum. Since some are now in use and others are being developed as time goes on, it seems appropriate to make known some of the results of studies by the Soil Conservation Service of devices of this type. This article deals only with tipping-bucket instruments with which the determination of rate of flow and total volume of flow is dependent upon the delivery of the bucket per tip.

These studies have shown that close control in the manufacturing and great care in the installing and servicing of these instruments are required to obtain flow measurements of even moderate accuracy. This is especially true for the measurement of sediment-laden runoff. Two other inherent characteristics of tipping-bucket gages, namely, a large head-room requirement and a limited capacity in flow range, add to the unsuitability of these devices for adoption for general use in the measurement of soil and water losses from experimental areas. This is not to say that satisfactory measurements cannot be made under some conditions.

A short article [PARSONS, 1941] on the behavior of a tipping-bucket rain gage has already been published; but, to give a more adequate basis for these conclusions, portions of a report (unpublished, by the present authors, Report on the calibration of a Lowdermilk tipping-bucket gage, June, 1935) on studies of a much larger instrument are here given. The data and the data analysis should help in an understanding of the more important factors that affect the behavior of operation. The necessary procedures for obtaining the best possible results from gages already in operation will be indicated.

The testing work was done by the writers at the Hydraulic Laboratory of the National Bureau of Standards as a part of a general program of the testing and developing of hydraulic devices for use in soil and water conservation research.

The gage calibrated was one of several constructed for the use of the U. S. Forest Service. It was known as the "large" tipping-bucket gage to distinguish it from a similar device of smaller capacity. Each side of the large tipping bucket had a nominal capacity of one-half cubic foot.

The tipping bucket is actuated by the runoff entering that side of the bucket presenting itself immediately below the entrance spout. When the weight of the runoff and the impact forces produced by the entering jet jointly exert a moment about the knife-edge fulcrum slightly in excess of that exerted by the weight of the bucket and its appendages, the bucket tips. This places the empty portion of the bucket below the spout and the process is repeated. When the gage is in field operation, each tip of the bucket is recorded on a clock-driven chart by an electrically actuated pen. The number of tips is also registered by a Veeder counter.

Test procedure--Each test was made at a steady flow. The water-supply system consisted of a pump, a constant level tank, a pipe supply line, and a valve that was used to change the flow between tests. A test consisted in the volumetric measurement in a calibrated tank of the flow through the tipping-bucket gage over a measured period of time. The period of time was chosen such that a whole number of tips occurred during the time. The measured volume divided by the number of tips gave the average volume of water discharged at each tip of the bucket.

A test series was a group of consecutive tests in which the flow through the gage was varied from test to test over the range from near zero to a large flow near the limit of capacity of the instrument. All variables other than rate of discharge were held constant during a test series. The variables that were altered between series were: (a) the angle of tip, α; (b) the counterweight attached, W_c; (c) the manner in which the flow was conducted into the bucket, that is, the entrance arrangement; (d) the amount of solid material in the gaged flow, that is, the effective density. The scope of the investigation and the values of the several variables were as shown in Table 1.

Table 1--Test series

Series	No. of tests	Angle of tip, α	Counterweight, W_c	Entrance arrangement	Liquid
		° ′	lb		
A	7	32 11	0.0	I	Clear water
B	7	32 18	4.5	I	Clear water
C	10	32 25	9.9[c]	I	Clear water
D	4	32 25	9.9	I	Clear water
E	9	29 47	0.0	I	Clear water
F	6	34 51	0.0	I	Clear water
G	6	32 37	0.0	II	Clear water
H	12	32 37	0.0	III	Clear water
I	16	30 06	0.0	III	Clear water
J (a)	8	32 32	0.0	III	Clear water
J (b)	3	32 32	0.0	III	Water carrying sand

[c] Counterweight free to swing for this series.

Measurements--The test measurements are summarized in Table 2. These measurements were supplemented by other kinds of measurements that were made to provide a basis for the analysis of the results that were obtained in the tests.

Among the supplemental measurements was a crude attempt to determine the time that elapsed between the beginning of tipping and the instant that the center partition of the bucket passed through the center of the entering jet. This time, as measured with a stop watch, ranged between 0.4 and 1.2 sec, decreasing with increasing flow through the gage.

Table 2--Test data

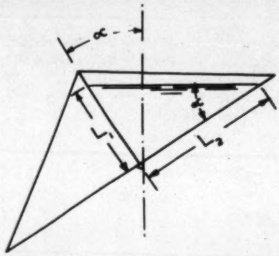
Test	Flow, Q	No. of buckets	Time	Buckets per min	Delivery, V	V/V_o
	cfs		sec		cu ft	
Series A - $\alpha = 32° 11'$, $W_c = 0$, Entrance I, Clear water, $V_o = 0.410$						
1	0.31709	222	433.0	30.8	0.6185	1.510
2	0.25021	. . .	584.8	(test incomplete)		. . . .
3	0.15703	290	956.1	18.2	0.5177	1.265
4	0.08734	300	1666.2	10.8	0.4851	1.185
5	0.03292	204	2794.4	4.4	0.4509	1.100
6	0.00563	28	2129.3	0.8	0.4277	1.044
7	0.24936	260	584.4	26.7	0.5605	1.369
Series B - $\alpha = 32° 18'$, $W_c = 4.5$, Entrance I, Clear water, V_o not measured						
8	0.3200	192	339.8	33.9	0.5663	1.533
9	0.2576	226	474.2	28.6	0.5405	1.465
10	0.1655	268	780.5	20.6	0.4820	1.306
11	0.10528	278	1181.0	14.1	0.4473	1.211
12	0.03421	210	2536.6	5.0	0.4132	1.119
13	0.00625	76	4735.7	1.0	0.3893	1.053
14	0.2586	222	450.6	29.5	0.5249	1.420
Series C - $\alpha = 32° 25'$, $W_c = 9.9$, Entrance I, Clear water, $V_o = 0.316$, swinging counterweight						
15	0.3365	228	326.2	41.9	0.4814	1.521
16	0.2609	238	449.3	31.8	0.4926	1.557
17	0.1653	282	696.5	24.2	0.4084	1.290
18	0.1050	302	1136.5	15.9	0.3953	1.249
19	0.03402	248	2622.4	5.7	0.3598	1.137
20	0.00601	39	2168.6	1.1	0.3348	1.058
21	0.3369	215	310.6	41.5	0.4867	1.538
22	0.3377	210	289.8	43.5	0.4661	1.473
23	0.2603	170	310.0	32.9	0.4747	1.500
24	0.2605	230	436.0	31.6	0.4938	1.561
Series D - $\alpha = 32° 25'$, $W_c = 9.9$, Entrance I, Clear water, $V_o = 0.316$						
25	0.3359	232	341.3	40.8	0.4941	1.560
26	0.2598	252	466.8	32.4	0.4813	1.520
27	0.1665	278	706.2	23.6	0.4228	1.334
28	0.10575	318	1175.9	16.2	0.3911	1.234
Series E - $\alpha = 29° 47'$, $W_c = 0$, Entrance I, Clear water, $V_o = 0.341$						
29	0.3228	240	350.2	41.1	0.4710	1.381
30	0.2616	234	442.8	31.7	0.4950	1.450
31	0.1663	284	696.8	24.5	0.4081	1.196
32	0.1044	322	1250.9	15.4	0.4058	1.190
33	0.03314	264	2961.4	5.4	0.3717	1.089
34	0.00597	96	5670.0	1.0	0.3524	1.033
35	0.2548	228	442.0	31.0	0.4940	1.448
36	0.2908	226	400.9	33.8	0.5159	1.512
37	0.2028	276	589.0	28.1	0.4328	1.268
Series F - $\alpha = 34° 51'$, $W_c = 0$, Entrance I, Clear water, $V_o = 0.508$						
38	0.3192	160	361.7	26.5	0.7215	1.420
39	0.2593	144	373.2	23.2	0.6719	1.322
40	0.1648	206	775.9	15.9	0.6202	1.221
41	0.1050	192	1086.7	10.6	0.5942	1.169
42	0.03340	196	3217.9	3.7	0.5484	1.080
43	0.00621	61	5172.7	0.7	0.5266	1.036

(Continued)

Table 2--Test data (concluded)

Test	Flow, Q	No. of buckets	Time	Buckets per min	Delivery, V	V/V_o
	cfs		sec		cu ft	
Series G - $\alpha = 32° 37'$, $W_c = 0$, Entrance II, Clear water, $V_o = 0.424$						
44	0.1007	232	1172.0	11.9	0.5086	1.200
45	0.4204	174	337.8	30.9	0.8162	1.926
46	0.3817	172	342.4	30.2	0.7598	1.793
47	0.1576	236	810.0	17.5	0.5410	1.277
48	0.2472	192	468.3	24.6	0.6029	1.423
49	0.02973	200	3083.5	3.9	0.4583	1.081
Series H - $\alpha = 32° 37'$, $W_c = 0$, Entrance III, Clear water, $V_o = 0.424$						
50	0.4479	170	231.7	44.0	0.6105	1.441
51	0.4226	172	249.6	41.3	0.6132	1.447
52	0.3855	170	280.1	36.4	0.6351	1.499
53	0.3400	184	354.9	31.1	0.6558	1.548
54	0.2650	234	520.7	27.0	0.5897	1.390
55	0.1698	200	646.0	18.6	0.5485	1.295
56	0.1089	214	995.0	12.9	0.5065	1.195
57	0.03415	294	3978.0	4.4	0.4621	1.091
58	0.1683	218	703.3	18.6	0.5430	1.281
59	0.2464	194	455.4	25.6	0.5783	1.364
60	0.3078	160	323.0	29.7	0.6214	1.467
61	0.006932	128	8073.0	1.0	0.4370	1.031
Series I - $\alpha = 30° 06'$, $W_c = 0$, Entrance III, Clear water, $V_o = 0.345$						
62	0.005223	118	8162.3	0.9	0.3613	1.046
63	0.03170	242	2942.6	4.9	0.3854	1.116
64	(test incomplete)					
65	0.3385	216	307.8	42.1	0.4824	1.398
66	0.3839	226	291.8	46.5	0.4957	1.436
67	0.2772	212	396.8	32.0	0.5188	1.502
68	0.2069	204	450.7	27.2	0.4570	1.324
69	0.1686	236	640.4	22.1	0.4576	1.326
70	0.1071	226	893.6	15.2	0.4235	1.226
71	0.3074	234	380.5	36.9	0.4999	1.450
72	0.2915	218	393.1	33.3	0.5256	1.521
73	0.2601	226	445.4	30.4	0.5126	1.485
74	0.2436	226	459.6	29.5	0.4953	1.435
75	0.2252	208	436.2	28.6	0.4722	1.368
76	0.1875	258	618.7	25.0	0.4496	1.301
77	0.1494	244	729.3	20.1	0.4464	1.292
Series J - $\alpha = 32° 32'$, $W_c = 0$, Entrance III, Water carrying sand, $V_o = 0.417$						
78	0.1670	156	511.4	18.3	0.5476	1.310
79[a]	0.1709	160	497.6	19.3	0.5315	1.271
80	0.1685	200	655.8	18.3	0.5524	1.322
81	0.2621	200	449.0	26.7	0.5884	1.410
82[a]	0.2665	190	407.7	28.0	0.5719	1.370
83	0.2611	196	440.3	26.7	0.5866	1.405
84	0.04639	120	1199.8	6.0	0.4638	1.109
85[a]	0.03521	200	2587.0	4.6	0.4554	1.090
86	0.04594	248	2513.8	5.9	0.4657	1.115
87	0.03495	240	3172.3	4.5	0.4620	1.106
88	0.1605	186	623.7	17.9	0.5383	1.289

[a] Sand in water; other results are for check tests with clear water.



Series	Values of L_1 and L_2				Calculated angle of tip $\alpha = \tan^{-1} L_1/L_2$		V_o = volume of water required to tip bucket at zero flow			
	North bucket		South bucket				North bucket		South bucket	
	L_1	L_2	L_1	L_2	North	South	Wt.	Vol.	Wt.	Vol.
	inch	inch	inch	inch	° '	° '	lb	cu ft	lb	cu ft
A	10.20	16.31	10.37	16.37	32 01	32 21	25.4	0.407	25.7	0.412
B	(Series B values are interpolated)				32 11	32 25	22.8	0.365	23.2	0.372
C and D	9.02	14.25	9.20	14.45	32 20	32 29	19.4	0.311	20.0	0.321
E	8.90	15.58	8.95	15.60	29 44	29 51	21.2	0.340	21.3	0.342
F	12.00	17.35	12.04	17.17	34 40	35 02	31.5	0.506	31.8	0.510
G and H	10.61	16.50	10.49	16.48	32 45	32 29	26.4	0.424	26.4	0.424
I	9.05	15.64	9.08	15.63	30 03	30 09	21.3	0.342	21.7	0.349
J	10.37	16.33	10.47	16.35	32 25	32 38	25.8	0.414	26.2	0.421

Fig. 1--Determination of zero-flow delivery and calculated angle of tip

The angle of tip was determined as the angle whose tangent was the ratio of two length measurements, as indicated in Figure 1. These length measurements, the calculated angle of tip, and the zero-flow delivery for each test series are also shown in Figure 1. It is important to note that the zero-flow delivery varied greatly between the series as a result of the variations in angle of tip and counterweight. The angle of tip was dependent upon the positions of the bumpers that limited the rotation of the bucket.

Values of the geometrical qualities of the tipping bucket are given in Figure 2. The position of the center of gravity of the bucket was determined by the intersection of plumb lines through two or more points about which the bucket was balanced. The geometry of the knife-edge bearing is shown in Figure 3.

Two of the three entrance arrangements that were used are shown in Figure 4. However, none of the three was subjected to field trials to show its suitability from the standpoint of passing trashy runoff flows. An entrance arrangement must be satisfactory in this respect before it can be otherwise considered for adoption.

The data for the three tests in which sand was fed into the flow are given in Table 3.

Table 3--Results of tests with water carrying sand

Test	Q	Rate of tipping	Sand load	Weight of mixture	Delivery of mixture	Clear water delivery[a]	Decrease in delivery due to sand load	
	cfs	buckets per min	pct by weight	lb per cu ft	cu ft	cu ft	cu ft	pct
79	0.171	19.3	4.4	64.1	0.532	0.550	0.018	3.3
82	0.266	28.0	4.0	64.0	0.572	0.600	0.028	4.9
85	0.035	4.63	4.8	64.3	0.455	0.460	0.005	1.1

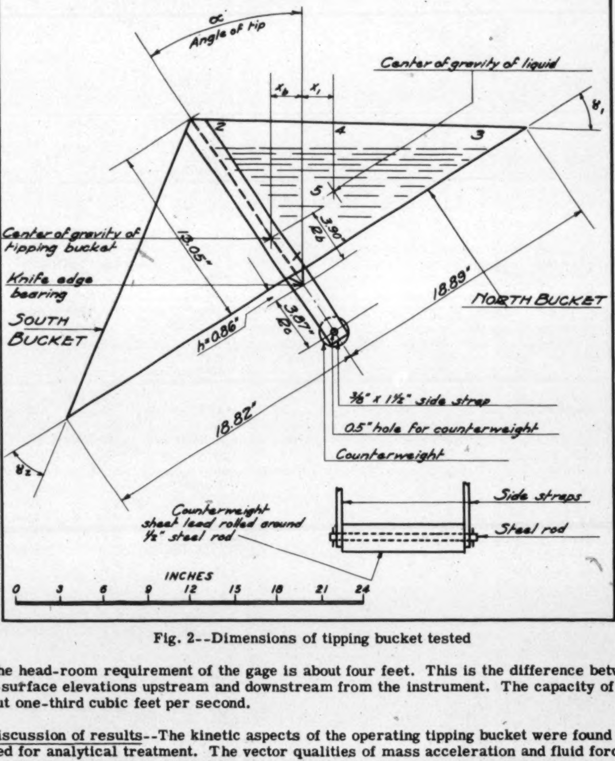
[a] Clear water delivery at given rate of tipping.

Inside width, b, at point	1	2	3	4	5	Mean
NORTH BUCKET	8.52"	8.44"	8.48"	8.26"	8.42"	8.42"
SOUTH BUCKET	8.55"	8.50"	8.62"	8.54"	8.55"	8.55"

Thickness of sheet metal, K, = 0.079"

Weight of Bucket (without counterweight) Wb = 30.4 lbs.

$\theta_1 = 34°42'$; $\theta_2 = 34°48'$



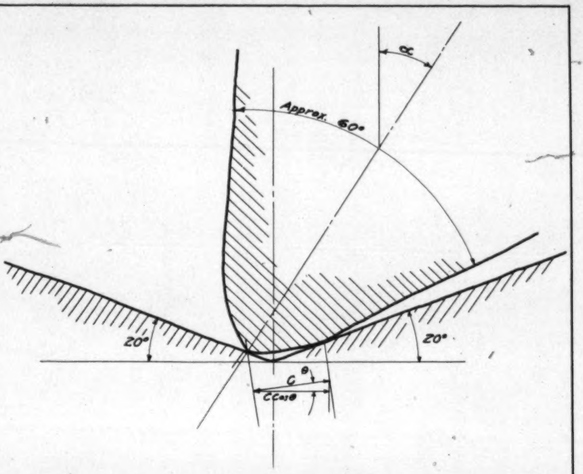
α
Angle of tip
Center of gravity of liquid
x_b
x_1
θ_1
2
4
3
5
Center of gravity of tipping bucket
13.05"
3.90"
R_b
Knife edge bearing
18.89"
NORTH BUCKET
SOUTH BUCKET
h = 0.86"
3.87"
R_c
3/8" x 1½" side strap
0.5" hole for counterweight
Counterweight
18.82"
θ_2
Side straps
Steel rod
Counterweight sheet lead rolled around ½" steel rod
INCHES
0
3
6
9
12
15
18
21
24

Fig. 2--Dimensions of tipping bucket tested

The head-room requirement of the gage is about four feet. This is the difference between the water-surface elevations upstream and downstream from the instrument. The capacity of the gage is about one-third cubic feet per second.

Discussion of results--The kinetic aspects of the operating tipping bucket were found to be too involved for analytical treatment. The vector qualities of mass acceleration and fluid forces associated with the entering jet affected the time required for tipping of the bucket and the moment of force about the fulcrum. Even though these qualities had not varied continuously with time, their evaluation would have been most difficult.

As a next best method for simplification of the results and understanding of the operation of the instrument, its behavior throughout the test range was compared with its behavior at a particular rate of tipping. The zero-flow delivery, or the amount of liquid required to tip the bucket at zero rate of tipping, is the logical unit to use in expressing the delivery at all other rates.



Angle α	MEASURED VALUES OF C			
	Affecting North Bucket		Affecting South Bucket	
	East bearing	West bearing	East bearing	West bearing
30°	.02"	.02"	.10"	.02"
32½°	.07"	.04"	.15"	.07"
35°	.08"	.09"	.21"	.09"

Fig. 3--Knife-edge bearing

This unit is actually calculable from measurements of the static qualities of the instrument and is easily measured by other means. Thus, the test data are shown as relative quantities in Figure 5.

The data representation of Figure 5 indicates that, within limits, the delivery of the bucket at each tip for any rate of tipping is known if the delivery is known for one rate. This is presumably true for tipping buckets in general if a rating curve has been obtained for a given bucket and entrance arrangement design by hydraulic tests, such as is indicated in Figure 5. This is a fortunate condition for users of tipping-bucket gages.

The deviation of the data for Entrance Arrangement II shows that the manner of entry of water into the bucket is a material factor in the delivery of the bucket at each tip, especially at high discharges. This fact makes it necessary to include the entrance arrangement as an integral part of a tipping-bucket device for the measurement of flows.

The results obtained for the smaller angles of tip also deviated from the main trend showing that there is a limit to the range in angle that should be used. On the other hand, there is a considerable range in angle of tip and moment of the bucket, as reflected in the variation of zero-flow delivery, in which the data follow closely the same trend.

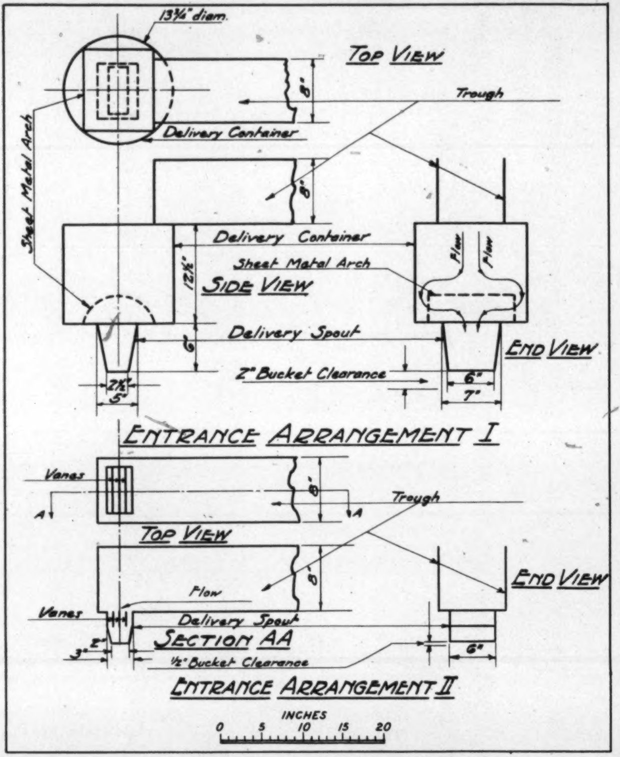

13¾" diam.
Top View
Trough
8"
Delivery Container
Sheet Metal Arch
8"
Delivery Container
Sheet Metal Arch
12½"
Side View
Flow
Flow
Delivery Spout
6"
End View
2" Bucket Clearance
2½"
5"
6"
7"
Entrance Arrangement I
Vanes
A
8"
Trough
A
Top View
8"
Flow
End View
Vanes
Delivery Spout
2"
Section AA
3"
½" Bucket Clearance
6"
Entrance Arrangement II
INCHES
0
5
10
15
20

Fig. 4--Entrance arrangements I and II

Now, since the delivery of the tipping bucket gage at all discharges is a function of the zero-flow delivery and zero-flow delivery can be calculated through consideration of the geometry of the gage, it is instructive to analyze the influence on bucket delivery of variations in the several factors involved. This has been done by equating expressions for the moment of force of the liquid in a bucket about the fulcrum to the moment of force of the several parts of the bucket and its appendages about the fulcrum. Then, by considering all but one of the factors constant the rate of change in bucket delivery with respect to variation in the uncontrolled variable was obtained by differentiation, giving for small variations the change in bucket delivery for a given change in the factor being considered. Table 4 shows the results of these calculations and comparable, experimental determinations of the influence of variations in angle of tip and counterweight.

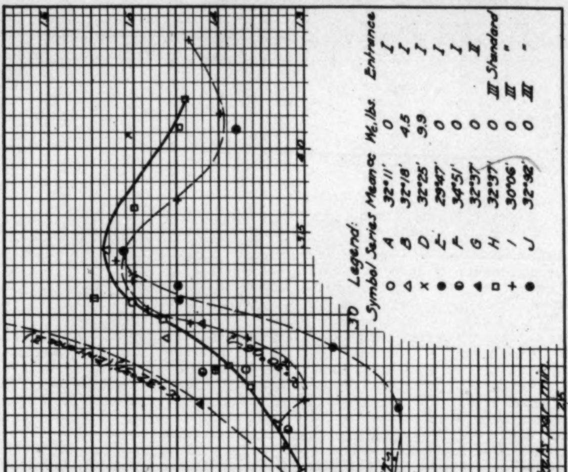


Fig. 5--Relation between rate of tipping and bucket delivery expressed in units of volume at zero flow

Conclusions--The following conclusions are drawn.

(1) The delivery per tip of the tipping-bucket changes with the rate of tipping.

(2) The measurement of flows with this instrument therefore requires: (a) a record of operation from which the rate of tipping can be obtained; (b) a calibration curve showing the relative bucket delivery for various rates of tipping.

(3) The entrance arrangement is an intergral part of a satisfactory tipping-bucket gage because the bucket delivery at high discharges is partially dependent upon the manner of entry of the liquid.

Table 4--Change in delivery with change in various factors

Quality	Increase in amount	Quantity	Consequent change in delivery	Experimental determination
		pct	pct	pct
Angle of tip	1 degree	. . .	8.2	8.0
Liquid density[a]	. . . .	1.0	-0.6	. . .
Counterweight	1 pound	. . .	-2.1	-2.0
Weight of bucket	1 pound	3.3	2.1[b]	. . .
Width of bucket	1/4 inch	2.9	1.5	. . .
Depth of bucket	1/2 inch	3.8	4.3	. . .
Length of bucket	1 inch	2.7	0.9	. . .
Distance from knife edge to bottom of bucket	1/32 inch	3.6	0.9	. . .
Thickness of bucket metal	0.015 inch[c]	19.0	9.2	. . .

[a] An additional effect due to a change in liquid density should be expected because of its influence on forces resulting from the deflection of the entering jet.

[b] Assuming that the extra weight is added so that R_b is unchanged.

[c] Equivalent to a change from 14-gage to 13-gage metal.

(4) Given a standardized design of the gage and a calibration curve, the influence of small variations in construction and installation of the instrument can be evaluated by a determination of the zero-flow delivery or the delivery at any other known rate of tipping.

(5) The bucket delivery is markedly affected by small changes in the angle of tip. Particular effort should therefore be made to insure the maintenance of a selected value for this factor.

(6) Particular care should be given to bearing construction to insure that the point of bearing will not change during operation of the instrument.

(7) The head-room requirement of about four feet for a flow of about one-third cubic feet per second is several times greater than is required for some other measuring devices.

(8) In consideration of (a) the care required in the construction and installation, (b) the head-room requirement, (c) the need for a record of rate of tipping, and (d) the moderate accuracy that is attainable, it is concluded that the device is not suitable for adoption for general use in the measurement of soil and water runoff.

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FURTHER STUDY OF ATMOSPHERIC PRESSURE FLUCTUATIONS RECORDED ON SEISMOGRAPHS

Maurice Ewing and Frank Press

(Lamont Geological Observatory, Columbia University, Contribution No. 77)

Abstract--The predominant background disturbance on a long-period vertical seismograph is removed by providing compensation for atmospheric pressure fluctuations. A seismically-compensated, long-period microbarovariograph for study of pressure oscillations in the range 20 - 2000 sec is described. Comparison of records from the pressure-compensated seismograph and the seismically-compensated microbarovariograph indicates that no significant ground motion is caused by direct coupling of atmospheric pressure fluctuations to the Earth. Sample records are shown.

Introduction--Beginning in November, 1950, Press and Ewing noticed that simultaneous disturbances were recorded on the long-period Benioff seismographs at Palisades and on a newly-installed Friez microbarograph. In a recent paper CRARY and EWING [1952] studied disturbances on the long-period vertical Benioff seismograph at Weston, Mass., and a sensitive microbarograph, and concluded that seismograph oscillations accompanying certain barometric disturbances could be accounted for by the effect of changes in atmospheric buoyancy on the inert mass of the seismograph and did not represent Earth movements. The present investigation was undertaken to confirm this conclusion and to examine three problems which are affected by it. (1) The development of a buoyancy-compensated, long-period vertical seismograph (T_o = 10 sec, T_g = 75 sec) would eliminate atmospheric pressure fluctuations as a major source of background noise and permit study of weak long-period seismic disturbances. (2) The construction of a device for the study of atmospheric pressure fluctuations in the period range 20 - 2000 sec, completely compensated for seismic movements, would facilitate study of atmospheric turbulence and wave propagation. (3) The comparison of records from a buoyancy-compensated seismograph and a seismically-compensated microbarovariograph offers a direct test of the suggestion made by some investigators that significant ground motion is caused by direct coupling of atmospheric pressure fluctuations to the Earth.

The general question of transfer of energy from the atmosphere to the Earth is of fundamental importance in all theories of the generation of microseisms. The results of this study confirm the theoretical prediction of very small coupling based on great contrast in acoustical impedance and also the empirical observation that storms over land are relatively ineffectual in producing microseisms.

The uncompensated seismometer had been built a few months before the present study started. Its usefulness was limited by severe background noise, which now has been greatly reduced by buoyancy compensation.

The seismically-compensated microbarovariograph was constructed to measure the atmospheric pressure fluctuations and prove that the indications of the seismograph agreed quantitatively with those calculated from buoyancy effects. Thus, the indications of the uncompensated seismograph were spurious, in that they did not correspond to ground motion. In the next step, buoyancy compensation was added to the seismograph, and the expected improvement in background noise level was realized. The compensated instrument has proved to be extremely valuable for earthquake study, and details of its performance will be given in a later paper. Comparison of simultaneous recordings of the microbarograph with first the uncompensated seismograph and later the compensated seismograph form the basic data of the present paper.

The microbarovariograph--This instrument (Fig. 1) actually measures the rate of change of air density, which is then related to pressure changes. Density fluctuations of the air are detected by measuring changes in the buoyancy of a hollow cylinder. This is accomplished by placing cylinders of identical volume on each end of a balance. One of the cylinders is sealed, while are has free access in and out of the other cylinder through a small opening. The balance is initially adjusted to a horizontal position. Changes in air density have no effect on the open cylinder but produce variations in the buoyant force exerted on the sealed cylinder by the atmosphere. Atmospheric density changes thus produce rotations of the balance about the zero position.

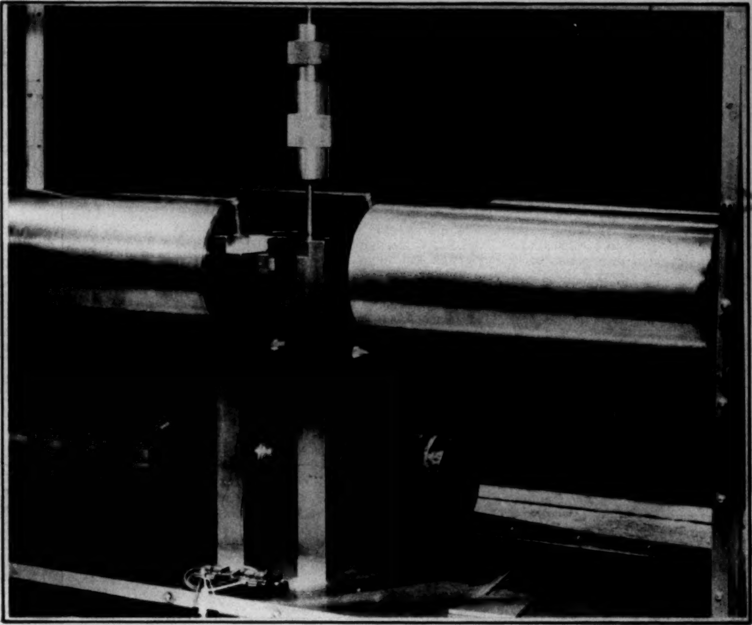

Fig. 1--Seismically-compensated microbarovariograph

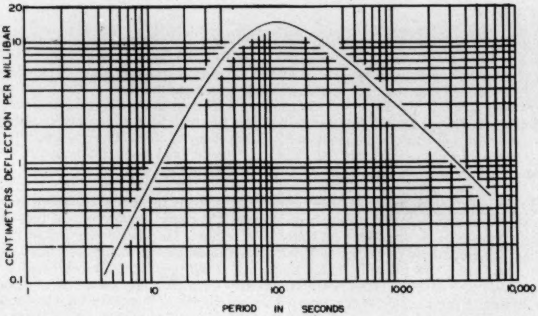

Fig. 2--Calibration curve of microbarovariograph assuming isothermal pressure variations

The free period of the system is adjusted by varying the distance of the center of gravity below the center of suspension. A coil attached at each end of the balance is surrounded by a radial magnetic field produced by an Alnico V cylindrical magnet-and-pole-piece assembly attached to the rigid instrument base.

Motion of the balance produces a voltage in the coils proportional to the rate of change of air density. Recording is accomplished by wiring the coils in a push-pull circuit directly coupled to a Benioff long-period galvanometer, and magnification is adjusted by varying the shunt and series resistance of the coupling network between the galvanometer and transducer. Expressions for the dynamic magnification and phase changes of atmospheric pressure fluctuations recorded by the instrument may readily be derived in a manner analogous to the corresponding expressions for ground displacements recorded by a seismograph [CHAKRABARTY, 1949] simply by replacing the ground-acceleration term by a term for the acceleration caused by the buoyancy change [CRARY and EWING, 1952]. Buoyancy changes are converted to atmospheric pressure changes by assuming an isothermal or adiabatic relation between pressure and density. The operating constants for the instrument at the Lamont Geological Observatory in Palisades, N. Y., are balance period T_0 = 10.5 sec, damping $\epsilon = 3.56\ \mathrm{sec}^{-1}$, galvanometer period T_g = 76 sec, and damping $\epsilon_g = 10\ \mathrm{sec}^{-1}$.

A steady-state calibration curve is shown in Figure 2, in which isothermal pressure variations are assumed. For adiabatic pressure changes, divide the ordinate by 1.4. Greater sensitivity is available simply by adjusting the coupling network. Long-period response may be improved by using a slow leak for access to the open cylinder and raising the gain. Vertical movements of the ground are of course dynamically balanced out and horizontal movements have negligible effect.

Figure 3(A) shows a recording made by the microbarovariograph on March 4-5, 1952. The trace has been made heavier for emphasis from 21h 00m to 22h 00m EST. Trace deflections are proportional to the first derivative of air pressure. Beginning at 21h 06m the instrument records large-amplitude pressure oscillations of about ten-minute period due to the passage of a pressure jump associated with a squall line. The corresponding record made by the standard Friez microbarograph which is directly sensitive to pressure is shown in Figure 3(B). It is seen that the new microbarovariograph permits more detailed study of the damped oscillations following the pressure jump. The prominent short-period turbulent pressure fluctuations disappear almost immediately after the passage of the pressure jump.

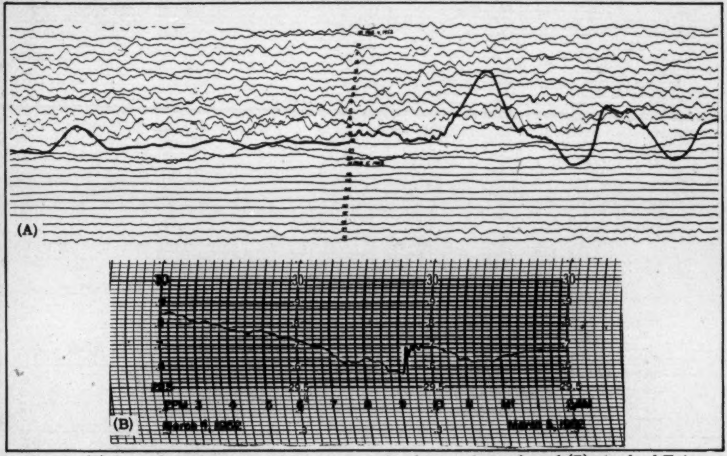

Fig. 3--(A) Recording of pressure jump on new microbarovariograph, and (B) standard Friez microbarograph; time marks are at one-minute intervals in 3(A)

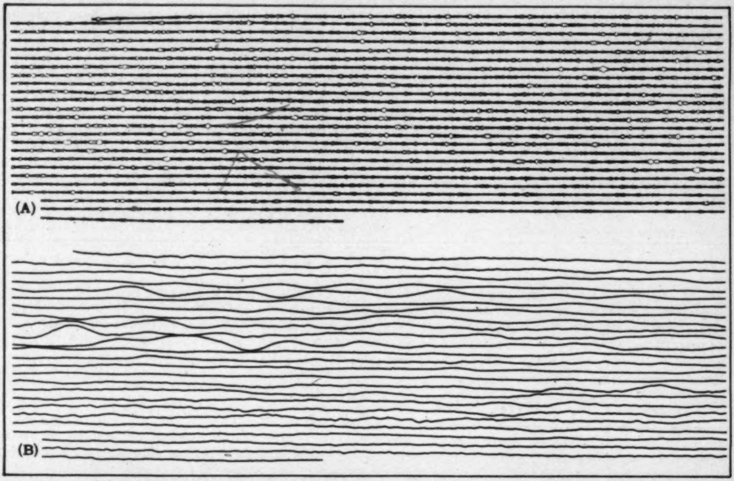

Fig. 4--(A) Simultaneous recordings from the compensated seismograph, and (B) from the microbarovariograph for Feb. 20-21, 1952; time marks are at one-minute intervals

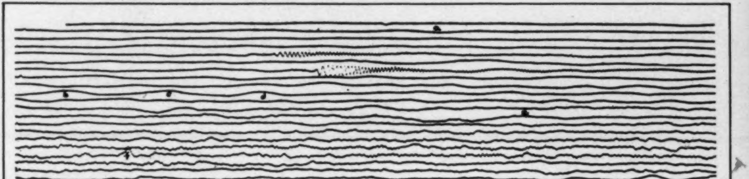

Fig. 5--(A) Simultaneous recordings from the uncompensated seismograph, and (B) from the microbarovariograph for Jan. 19-20, 1952; time marks are at one-minute intervals

Figure 4B shows trains of long sinusoidal waves of periods up to ten minutes recorded on the microbarovariograph. The nature of these waves has not yet been established and is the subject of further investigation.

The compensated seismograph--The Columbia University long-period seismograph was constructed to provide instrumentation for the study of long-period body waves and Rayleigh waves. The seismometer incorporates a design originally suggested by LACOSTE [1934] for the use of a zero-length spring. It is presently operated with $T_o = 10$ sec, $T_g = 75$ sec, the galvanometer and seismometer being over damped. Operation of the pendulum at long periods is readily attainable.

Shortly after installation in November, 1951, it was noticed that the predominant long-period noise level recorded by the instrument was related to atmospheric pressure fluctuations. It seemed almost certain that these were the buoyancy effects mentioned above. The microbarovariograph was built to settle the question.

Comparison of records from the microbarovariograph and the seismograph verified the calculations. Figure 5 shows recordings from (A) the uncompensated seismograph, and (B) the microbarovariograph, aligned in time for January 19-20, 1952. An upward deflection in each record relates to the response to an impulsive upward ground movement or pressure increase, as is customary. Typical pressure fluctuations and the corresponding seismographic disturbances are indicated by letters. It is seen that there is an almost perfect time, wave shape, and phase correspondence between the two instruments, pressure increases being accompanied by upward motion of the seismometer boom (downward motion of the ground). Moreover, teleseismic motion recorded by the seismograph, as indicated by the earthquake surface waves, is absent on the microbarovariograph.

The seismograph was subsequently compensated for pressure fluctuations in a manner similar to the compensation of gravity meters. A sealed one-liter chemical flask was attached to an extension of the boom on the side of the hinge opposite the inert mass (Fig. 6). The distance from the flask to the hinge was determined so as to exactly balance out the torque of the buoyant force, due to the inert mass, boom, and coil. Simultaneous records from the compensated seismograph and the microbarovariograph are shown in Figures 4A and B respectively. Unlike the records of Figure 5, atmospheric pressure fluctuations recorded on the microbarovariograph are absent on the compensated seismograph.

Large-amplitude short-period pressure fluctuations are recorded occasionally on the compensated seismograph, in phase with the corresponding disturbance on the microbarovariograph (ground moves up with increase of pressure). Prior to compensation these disturbances were out of phase on the two instruments. It is believed that the compensated seismograph responds to these oscillations since the center of buoyancy is at the hinge (consisting of two wires in tension), and vertical motion at the hinge introduces an alternative mode of vibration which is pronounced near the free period of the pendulum. This effect can be removed by providing a suitable hinge constrained to rotations only or by placing the seismometer in a case of sufficiently tight construction to exclude the shorter period pressure fluctuations. The latter remedy has been tried with the result that pressure fluctuations recorded by the microbarovariograph are absent on the seismogram.

Conclusions--The following conclusions are drawn:

(1) Great improvement in the performance of a long-period vertical seismograph has been obtained by elimination of the effect of buoyancy of the atmosphere. A further report on the performance of this seismograph is in preparation.

(2) A sensitive microbarovariograph suitable for the study of atmospheric pressure fluctuations in the period range 20 to 2000 sec has been constructed. It records the strong turbulence associated with some air masses, and also records trains of sinusoidal waves, periods three to 20 minutes, which are the object of future study.

(3) Simultaneous operation of the seismograph and the microbarovariograph confirms the theory that energy transfer between atmosphere and Earth is very slight. Properly compensated instruments separate in a perfectly definite way atmospheric disturbances from Earth disturbances. The only cases in which energy transfer has been shown to exceed that predicted from simple considerations of acoustical impedance contrast are those of resonant coupling reported by PRESS and EWING [1951] and BENIOFF, EWING, and PRESS [1951].

Acknowledgments--The microbarovariograph was constructed by Angelo Ludas from initial drawings by Bernard Luskin with modifications by Vincent Jennemann. The long-period compen-

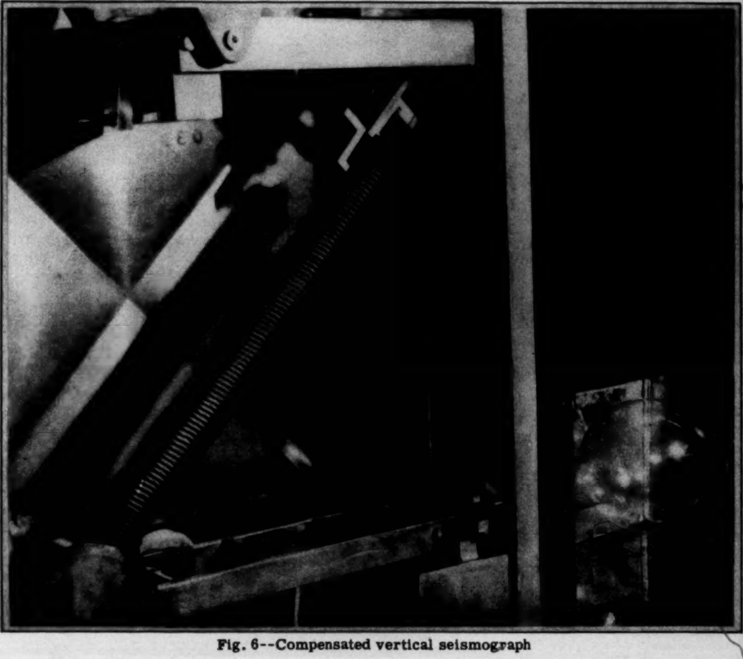

Fig. 6--Compensated vertical seismograph

sated seismograph was constructed by Louis Collyer. Harold Smith aided in the installation and operation of the instruments. We are grateful to the U. S. Weather Bureau for their cooperation in this project. This investigation has been supported by the Geophysics Research Division of the Air Force Cambridge Research Center under Contract AF 19(122)441.

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EXPANSION AND INCREASE IN PERMEABILITY OF CARBONATE ROCKS ON HEATING

John C. Maxwell and Peter Verrall

Abstract--Specimens of marbles, limestones, and travertine, heated at one atmosphere and at 5000 and 10,000 lb/in^2 confining pressures, all showed permanent expansion, and of the same order of magnitude even at the highest pressure. Permeability of samples to water solutions (red and blue inks) increased markedly with heating. The mechanism may explain apparent high permeability of carbonate rocks to ore-bearing solutions when these same rocks have very low permeabilities at room temperatures.

Introduction--Limestone, marble, and other carbonate rocks near intrusive igneous bodies are commonly silicated or silicified and replaced by ore minerals and gangue to a considerable distance from the igneous rock. Away from the intrusive, the replacement may be related to recognizable fractures or fissures. Closer in, however, the carbonate rock may be totally replaced in a manner suggesting intimate permeation and movement of considerable quantities of solution through this part of the rock.

The difficulties involved in moving large quantities of fluids through massive limestone and marble have been discussed by BROWN [1947]. Under near-surface conditions of temperature and pressure the Grenville marble of the Balmat and Edwards districts, New York, has very low porosity and the existing pores are mostly of capillary and sub-capillary size. Pressure of several hundred lb/in^2 is insufficient to force water through the rock except along visible openings. This statement is probably true for most massive carbonate rocks; hence, there is a very real difficulty in explaining massive replacement of carbonate rocks. OHLE [1951] also found that limestones and dolomites in general were relatively impermeable but noted that the altered, ore-bearing carbonate rock was considerably more permeable.

Experiments performed on carbonate rocks by RALEIGH [1937], ROSENHOLTZ and SMITH [1949, 1950], and SCHAD [1917] suggest a mechanism whereby the permeability of the carbonate rock may be greatly increased at the time when the replacing solutions are most abundantly available, presumably after the intrusive has been emplaced and has begun to cool. These experiments show that carbonate rocks expand permanently when heated to temperatures of about 70°C or higher. Furthermore, the permeability increases markedly as the rock expands, as shown by the rate of penetration of dyes into the unheated samples.

Raleigh attributed the permanent expansion to the interaction of the calcite grains when heated. The thermal expansion of calcite is strongly anisotropic. Heating will, therefore, set up intergrain stresses and the ultimate effect will be loosening of grain boundaries and opening of cleavages. If the temperature is high enough (about 700°C), the grains may be so loosened that the rock crumbles.

Experiments--Similar heating experiments have been made at Princeton on various kinds of carbonate rocks (see Table 1) including Vermont white marble (West Rutland, and marbles A and B), Boone limestone from Missouri, Redwall limestone from Arizona, St. Genevieve oolitic limestone from Tennessee, and banded travertine also from Tennessee. Specimens of silicated marble from the Gouverneur district of New York were also used and gave comparable but erratic results due to poor measuring techniques. The effect of confining pressure on permanent expansion due to heating was also investigated.

Five series of experiments were carried out, as described in detail below. An electric muffle furnace with a Gardsman electronic controller was used in heating the specimens to the desired temperatures. A small hand-operated hydraulic pump provided pressure for Experiments 3 and 4. In all cases the confining fluid was distilled water. Permanent elongations were measured at room temperature; readings were not taken during the actual heating and cooling cycle. In experiments involving high pressure, the pressure was applied before the heating began; it was maintained as nearly constant as possible during the heating and cooling cycles and was released only after the bomb had been brought to room temperature. In general, heat was applied only long enough to bring the samples to the required temperature since it was found that much longer periods of heating had no measurable effect on the resulting permanent expansion.

Table 1--Permanent elongation, in per cent; atmospheric pressure

No.	Rock	Orientation[c]	Per cent elongation resulting from temperature shown							
			100°C	150°C	200°C	300°C	400°C	500°C	600°C	700°C
1	W. Rutland marble	⊥F	0.00	-0.01	0.02	0.10	0.29	0.58	0.80	1.41
2	W. Rutland marble	⊥F	0.02	0.01	0.04	0.18	0.37	0.62	0.86	1.52
3	W. Rutland marble	∥F (a)	0.03	0.01	0.06	0.19	0.30	0.42	0.71	1.10
4	W. Rutland marble	∥F (a)	0.06	0.06	0.07	0.20	0.28	0.40	0.66	0.99
5	W. Rutland marble	∥F (b)	-0.02	0.00	0.02	0.12	0.21	0.38	0.62	0.97
6	W. Rutland marble	∥F (b)	0.00	0.02	0.04	0.13	0.30	0.46	0.64	1.16
7	Boone limestone	⊥F	0.00	0.00	0.05	0.10	0.23	0.48	0.85	1.23
8	Boone limestone	⊥F	0.00	0.00	0.01	0.02	0.08	0.17	0.39	0.73
9	Boone limestone	∥F	-0.02	0.01	0.03	0.06	0.11	0.30	0.66	1.08
10	St. Genevieve limestone	⊥F	0.00	0.02	0.01	0.05	0.16	0.55	0.71	...
11	St. Genevieve limestone	⊥F	0.00	0.01	0.01	0.02	0.16	0.45	0.67	...
12	St. Genevieve limestone	∥F	-0.01	0.00	0.01	0.01	0.19	0.49	0.69	...
13	St. Genevieve limestone	∥F	0.03	0.07(?)	0.07	0.11	0.24	0.50	0.75	...
14	Travertine	⊥F; ∥X	-0.03	0.01	0.01	0.02	0.12	0.24	0.45	...
15	Travertine	⊥F; ∥X	-0.02	0.04	0.02	0.00	0.08	0.20	0.38	...
16	Travertine	∥F; ⊥X	0.00	0.02	0.01	0.13	0.42	0.79	1.05	...
17	Travertine	∥F; ⊥X	0.02	0.15	0.10	0.16	0.40	0.76	1.03	...
18	Marble A	⊥F	0.00	0.03	0.03	0.15	0.36	...	...	...
19	Marble A	∥F	0.02	0.04	0.07	0.23	0.40	0.65	1.00	...
20	Marble A	∥F, ⊥19	0.02	0.04	0.07	0.19	0.36	0.58	0.88	...
21	Marble B	⊥F	0.02	0.06	0.13	0.29	0.51	0.71	1.11	...
22	Marble B	∥F	0.01	0.03	0.07	0.17	0.32	0.47	0.71	...
23	Marble B	∥F, ⊥22	-0.01	0.02	0.07	0.23	0.47	0.70	1.07	...

(a) and (b) signify mutually perpendicular direction. [c]⊥F is perpendicular to foliation or bedding; ∥F is parallel to foliation or bedding; X is with respect to direction of crystal elongation, perpendicular or parallel, as designated by symbol.

The bombs used by Tozzer in Experiment 3 were sealed by a soft steel plug held against a shoulder in the mouth of the bomb by a second threaded plug. This type of closure was not too satisfactory as leaks tended to develop at high pressure. In Experiment 4 the specimens were enclosed in aluminum foil and placed in copper tubes of 1/16 inch wall thickness, formed to the approximately square cross section of the specimens in such a manner that the latter were a push-fit in the tubes. The tubes which were 4 1/2 inches long were sealed at the lower end by brazing, and were flanged at the upper end. The flange rested on the plug seat when placed in the bomb, acting effectively as a copper washer between the plug and its steel seat. The plug served also to seal the upper end of the tube during the experiment, preventing water from reaching the specimens.

For Experiments 1 and 2, oriented cores 3/4 inch in diameter and one inch long were cut with a diamond core drill. Three cores were cut at right angles to each other in each sample, one perpendicular to the foliation of the sample and the other two in the plane of the foliation. The ends of the specimens were squared off with a diamond saw. For Experiment 3, similarly oriented prisms approximately 2 3/4 inches long by 1/4 inch square were cut with a rock saw. Specimens for Experiment 4 were similar to those of Experiment 3, except that they were one inch long and were all cut with the length perpendicular to the foliation of the sample. For Experiment 5, one inch cubes were cut on the rock saw with one pair of cube faces parallel to bedding or foliation; the specimens from Experiment 4 were also used.

The initial lengths of the specimens and lengths after heating and cooling were measured by micrometer caliper gages reading to 0.0001 inch by interpolation. Each measurement represents an average of four or five readings.

Experiment 1--Oriented specimens of different rock types were progressively heated at atmospheric pressure in steps of 100°C from 100° to 700°C, with an intermediate step at 150°C. After each step the specimens were allowed to cool and their permanent elongation measured (see Table 1). All of the specimens showed permanent elongation of the same order of magnitude on

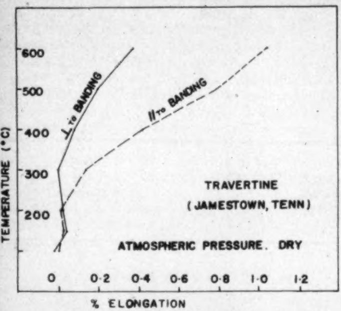

Fig. 1--Permanent elongation of travertine after heating to indicated temperature at atmospheric pressure; note effect of preferred orientation of calcite crystals

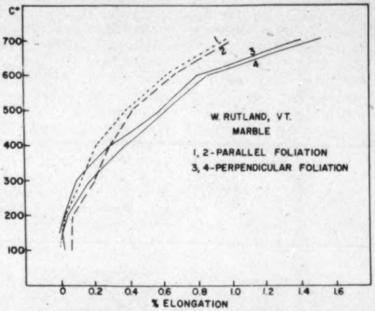

Fig. 2--Permanent elongation of West Rutland, Vt., white marble; note effect of preferred orientation

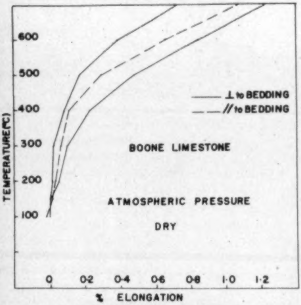

Fig. 3--Permanent elongation of Boone limestone; no apparent preferred orientation

heating, this elongation increasing non-linearly with temperature. Preferred orientation of the individual grains has a considerable effect on the amount of permanent elongation. As shown by Figure 1, the almost perfect parallel orientation of crystals in travertine is reflected in a large difference in permanent elongation of specimens oriented parallel and perpendicular to the crystal orientation. (Greatest length of crystals is perpendicular to banding.) The less perfect preferred orientation in a weakly foliated marble produces less marked differences in elongation (see Fig. 2), and this random orientation of calcite crystals in a limestone is demonstrated by Figure 3. The effect of preferred orientation was also noted by ROSENHOLTZ and SMITH [1949]. Thin sections show that the expansion is accompanied by separation of grains and opening of cleavages. At 700°C the samples assume a chalky appearance indicating decomposition, but at lower temperatures there is no evidence of decomposition.

Experiment 2--Specimens of West Rutland marble were subjected to a cyclic reheating process, as indicated in Table 2. Each specimen was heated twice at

Table 2--West Rutland marble, cut perpendicular to foliation; heated at atmospheric pressure; permanent elongation in per cent

Specimen	Cycle 1			Cycle 2		
	Temperature	Time	Permanent elongation	Reheated to	Time	Additional elongation
	°C	min	pct	°C	min	pct
1	500	10	0.70	500	10	0
2	400	52	0.41	400	76	0.03
3	400	52	0.42	400	76	0.08
4	300	33	0.25	300	105	0
5	200	30	0.17	200	1340	0
6	200	30	0.17	200	1340	0

a predetermined temperature, and after each cycle was allowed to cool and the permanent elongation measured. The experiment was carried out at atmospheric pressure. It will be seen from Table 2 that repetition or prolongation of heatings of the samples produced no significant change in the total elongation. The elongation of West Rutland marble at atmospheric pressure appears to be solely a function of temperature and orientation of the calcite grains. ROSENHOLTZ and SMITH [1949, 1950] in experiments on Yule marble and Crestmore sky blue marble obtained appreciable values for additional permanent expansion on second cycle heating to 700°C, which they attribute to strains due to the anisotropic expansion of the calcite grains. The first cycle permanent expansion they believe to be due largely to release of internal stress by the heating.

Experiment 3--Unjacketed specimens of marbles A and B of various orientations were heated to temperatures of from 200° to 500°C while held under a hydrostatic pressure of 5000 lb/in^2 in a steel bomb [TOZZER, 1951]. The pressure-transmitting fluid (water) was free to penetrate the specimens during the process. Pressure was applied prior to heating and was maintained during cooling of the specimens to room temperature. The permanent elongations were measured as before and are tabulated in Table 3. For similar temperatures, these are somewhat greater than elongations found in Experiment 1, the increase in some cases being of the order of 100 pct. The elongation curve for marble B is given in Figure 4 (marked 5000 wet). In this series of experiments the pressure fluid was free to penetrate along grain boundaries and cleavages; hence, the confining pressure was actually applied to individual grain surfaces rather than to the outer surface of the specimen.

Table 3--Permanent elongation in per cent at 5000 lb/in^2, pressure fluid (water) in contact with specimen

No.	Rock	Orientation[a]	Per cent elongation resulting from temperature shown			
			200°C	300°C	400°C	500°C
1	Marble A	⊥F	0	0.43	0.81	0.96
2	Marble A	∥F	-0.07	0	0.61	0.83
3	Marble A	∥F, 2	0	0.31	0.38	1.05
4	Marble B	⊥F	0	0.10	0.66	0.77
5	Marble B	∥F	0.12	0.04	0.65	0.81
6	Marble B	∥F, 5	0.01	0.31	0.49	0.93

[a] ⊥F is perpendicular to foliation or bedding; ∥F is parallel to foliation or bedding.

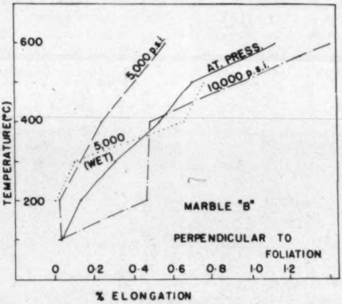

Fig. 4--Permanent elongation of Vermont white marble heated at atmospheric pressure, at 5000 lb/in^2 in contact with water, and at 5000 and 10,000 lb/in^2 with water excluded from the specimen

Experiment 4--For Experiment 4, specimens cut perpendicular to the foliation of the rock were encased in copper jackets, one specimen of each of the three rocks being placed in each jacket. The purpose of the jacket was to prevent the water in the bomb from penetrating the specimens during the experiment. The jackets were placed in the bomb, pressures of 5000 or 10,000 lb/in^2 applied, and then the bomb was heated in the furnace at temperatures up to 600°C. Pressure was released after the specimens had been cooled to room temperature, and permanent elongation measured as before. Results are tabulated in Table 4 and typical curves illustrated by Figures 4 and 5. They indicate, as might be expected, that the expansion after heating to a given temperature is less at 5000 lb/in^2 confining pressure than at atmospheric pressure. The expansion at 10,000 lb/in^2, however, is rather greater than for that at atmospheric pressure. The authors feel that this phenomenon may be due to an unequal distribution of pressure around the specimens during the experiment. The specimens were separated by layers of carborundum powder, and the same material was used to fill the jacket to the flange level above the upper specimen. The pressure inside the copper jacket probably was not truly hydrostatic.

Table 4--Permanent elongation in per cent, 5000 and 10,000 lb/in^2 fluid not in contact with specimen; specimens cut perpendicular to foliation

No.	Rock	Pressure	Per cent elongation resulting from temperature shown			
			100°C	200°C	400°C	600°C
1	Marble B	5,000	0.03	0.02	0.24	0.57
2	Redwall limestone	5,000	0.01	0.08	0.26	0.62
3	St. Genevieve limestone	5,000	0.07	0.14	0.18	0.47
4	Marble B	10,000	0.02	0.46	0.48	1.41
5	Redwall limestone	10,000	0.05	0.18	0.26	0.35
6	St. Genevieve limestone	10,000	0.06	0.01	0.34	. . .

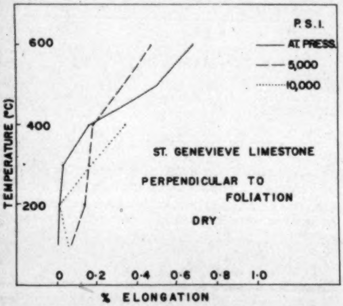

Fig. 5--Permanent elongation of St. Genevieve oolitic limestone heated at atmospheric pressure and at pressures of 5000 and 10,000 lb/in^2 with water excluded from the specimen

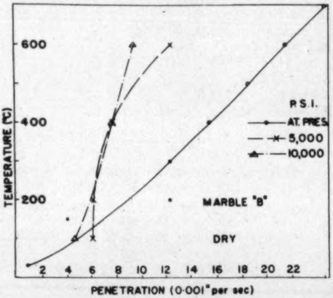

Fig. 6--Penetration of ink into Vermont white marble, in thousandths of an inch per second, after heating at indicated temperature and pressure; penetration measured at room temperature and atmospheric pressure

Experiment 5--The specimens used in Experiment 4 were immersed in blue ink for a period of ten seconds and immediately dried with paper towels and set aside to dry completely. They were then sawed across the center perpendicular to their lengths. A pencil mark was immediately drawn around the inside edge of the annular ink mark thus exposed. Average depths of penetration of the ink were measured by taking at least four measurements between the outside of the specimen and the pencil mark, perpendicular to the faces of the prisms. Measurements were made to the nearest 1/64 inch, though a certain judgment had to be used in cases where the ink mark was somewhat irregular. This same process was also carried out on the one-inch cubes especially prepared for this experiment. These were first heated to the required temperatures at atmospheric pressure, and allowed to cool. The results, taken as a measure of the permeability of the specimens, are listed in Table 5, and a typical set of curves is given by Figure 6.

These results show that permeability increases with the temperature to which the specimen has been heated, provided that the pressure is constant. No satisfactory conclusions can be drawn as to the effect of pressure on permeability, as the specimens of Experiment 4 were of considerably different size and shape from those heated at atmospheric pressure, thus probably changing the conditions for the penetration of the ink. Relative values of elongation are so similar for experiments at atmospheric pressure and at 5000 and 10,000 lb/in^2 confining pressure that it seems the permeabilities should be much closer than indicated. There does, however, seem to be a general tendency for permeability to decrease with pressure, other conditions being equal.

Summary and conclusion--Results of these experiments indicate that calcite-bearing rocks will expand permanently when heated 100° to 200°C or more above their normal temperature. This expansion takes place with confining pressures as great as 10,000 lb/in^2, whether or not the pressure fluid is in contact with the rock. The permeability of the rock to water solutions is

Table 5--Penetration of ink into specimen, in thousandths of an inch per second-after heading at indicated temperature and pressure and cooling to room temperature; penetration measured at atmospheric pressure

Rock	Pressure	Penetration at temperature shown								
		Unheated	100°C	150°C	200°C	300°C	400°C	500°C	600°C	700°C
	lb/in^2									
Marble B	15	0.8	...	3.9	12.5	12.5	15.7	18.8	22.0	25.0
Marble B	5,000	...	6.3	...	6.3	...	7.8	...	12.5	...
Marble B	10,000	...	4.7	...	...	...	7.8	...	9.4	...
St. Genevieve oolite	15	0.8	...	3.1	3.1	6.3	9.4	15.7	22.0	18.8
St. Genevieve oolite	5,000	...	0.8	...	1.6	...	3.9	...	4.7	...
St. Genevieve oolite	10,000	...	1.6	...	3.9	...	4.7	...	...	...
Redwall limestone	15	0.0	...	...	3.1	...	11.0	...	12.5	...
Redwall limestone	5,000	...	0.8	...	1.6	...	3.1	...	4.7	...
Redwall limestone	10,000	...	1.6	...	2.3	...	1.6	...	3.1	...

markedly increased as the rock expands with higher temperatures, though apparently the permeability is lowered somewhat by confining pressure. Preferred orientation of mineral grains is reflected in differences in permanent elongations of specimens cut perpendicular and parallel to foliation. Presumably there would be corresponding differences in resulting permeability, though this has not been demonstrated by our experiments.

The permanent expansion of carbonate rocks on heating is probably of importance in the formation of replacement deposits in such rocks. Transfer of heat to the carbonate rocks could occur either by conduction near an intrusive body or by passage of hot gases and solutions along fissures. In the first case, giving rise to contact metamorphism, the rock immediately surrounding the intrusive would be heated to the highest temperature and hence would be most expanded and most permeable to solutions given off by the magma. If these solutions are capable of dissolving carbonates, the permeability would increase with passage of quantities of solutions. In this connection, OHLE [1951] notes that ore-bearing carbonate rocks are generally more porous than barren rocks nearby. Massive replacements should result from this process. In the case of flowage of hot solutions along fissures the carbonate rock would be most permeable near the fissures and replacement should be localized along such fissures. Both types of occurrence of ore mineralization are common.

Acknowledgments--We are indebted to L. C. Tozzer for results described in Experiment 3 of this paper, and to W. H. Pool for assistance in the early phases of the work. The research was supported by funds of the Eugene Higgins Trust allocated to Princeton University.

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ON STRAIN ENERGY AND STRENGTH IN THE EARTH'S UPPER MANTLE

K. E. Bullen

Abstract--Considerations of strain energy suggest that either the Gutenberg-Richter magnitude formula gives the energy of large earthquakes too great by a factor rather greater than ten, or that the fracture-resisting strength of the material in the focal region of the greatest deep earthquakes is at least of order 500/kg/cm^2. It is suggested further that $SR^{1/2}$, where S denotes the breaking strength and R the volume of the strained material just prior to an earthquake, has for the greatest deep earthquakes a value at least half that for the greatest shallow earthquakes.

Introduction--In a discussion [COLLOQUIUM, 1951, p. 526] on forces in the Earth's upper mantle, it was stated that, since the duration of the main disturbance in the focal region of a deep earthquake is at most ten seconds while the velocity of propagation is of order 10 km/sec, the order of magnitude of the maximum volume of the focal region would be given by a sphere of radius 100 km. It was stated further that the shear stress which must be held by the material near a deep earthquake focus is estimated to be of the order of 10 to 100 kg/cm^2 and that from this data an estimate of the seismic energy can be derived.

Seismic energy and the strength and volume of the strained region--It is of interest to consider the above data in relation to a modified form of a calculation made by the writer a few years ago [BULLEN, 1947, p. 244]. Defining distortional strain and stress tensors E_{ij} and P_{ij} as excess effects above the mean normal stress and strain, so that

$$E_{ij} = e_{ij} - (1/3)\, e_{kk}\, \delta_{ij} \qquad (1)$$

$$P_{ij} = p_{ij} - (1/3)\, p_{kk}\, \delta_{ij} \qquad (2)$$

it is shown that the corresponding distortional strain energy U in a given volume is given by

$$U = \iiint \mu E_{ij}^2 \, d\tau \qquad (3)$$

where μ denotes the rigidity, and the integral is taken through the volume; the summation convention is understood. A simplified form of (3) has been used by BENIOFF [1951] in his discussion of strain characteristics of earthquake sequences. It can similarly be shown that the dilatational strain energy V in the volume is given by

$$V = (1/2)\iiint k\theta^2 \, d\tau \qquad (4)$$

where k denotes the incompressibility and θ the dilatation.

At points at which fracture is on the point of occurring the scalar P_{ij}^2 is equal to S^2, where S is a measure of the fracture-resisting strength; at other points $P_{ij}^2 = \alpha S^2$ where $0 \leq \alpha < 1$. It can be deduced from (1), (2), and the usual stress-strain relations that $P_{ij} = 2\mu E_{ij}$, so that by (3)

$$U = (1/4)\iiint \alpha \mu^{-1} S^2 \, d\tau \qquad (5)$$

Now let the volume in question be the region of strain in the vicinity of the focus of an earthquake just before the earthquake occurs. In general, the total strain energy U + V will not all be released with the one earthquake because of the occurrence of aftershocks. Also a considerable proportion of the released energy may be dissipated as heat instead of going into seismic waves (some of this heat energy is likely, of course, to contribute to the occurrence of aftershocks). It may be remarked that the dilatational strain energy V will be expected to be of the order of the distortional strain energy U, or possibly less, in the normal type of earthquake. In these circumstances we may put U = qE, where E is the energy released in seismic waves with the earthquake and q would be of order not less than 0.5 if there were no aftershocks and if no energy were dissipated, but more probably is of appreciably higher order. Taking μ and S to be uniform over the strained region and putting α equal to unity, we derive from (5)

$$4q\mu E = S^2R \qquad (6)$$

where R is the volume that would have been strained just before earthquake if the material were at breaking point throughout; in practice, the strained volume would, of course, be greater than R.

Application to the greatest known deep earthquake--Now apply (6) to the earthquake of May 26, 1932 (ϕ = 25°.2 S, λ = 179°.2 E), which is given by GUTENBERG and RICHTER [1949] as the greatest known earthquake with focal depth near 600 km. At this depth [BULLEN, 1947, p. 220] the value of μ is 1.3×10^{12} dynes/cm^2. The magnitude M of the earthquake is given by Gutenberg and Richter as 7 3/4, for which their formula [GUTENBERG and RICHTER, 1949]

$$\log_{10} E = 12 + 1.8\ M \qquad (7)$$

yields $E = 10^{26}$ ergs. If we (arbitrarily) put q = 2, (6) then gives

$$S^2R = 10^{39}\ \text{dynes}^2/\text{cm} \qquad (8)$$

If S is put equal to 10^8 dynes/cm^2 (corresponding to the value of 100 kg/cm^2 mentioned in the Introduction), (8) yields $R = 10^{23}\ \text{cm}^3 = 10^8\ \text{km}^3$. Even if we assume that R gives the order of the volume of the focal region of the earthquake, the value just yielded is more than 20 times the maximum volume quoted in the Introduction for the focal region.

This discrepancy can be formally removed if we both reduce q to unity, thereby assuming that most of the strain energy is converted into seismic wave energy with little heat dissipation, and also reduce E by a factor of 10 which is of the order of the minimum uncertainty assigned by Gutenberg and Richter to energy estimates based on their magnitude scales. (Gutenberg and Richter state that $\log_{10} E$ as given by (7) "may be in error by one unit or even more.")

Such a formal procedure does not, however, appear to be adequate for practical purposes since it is to be expected that the original strain energy would be spread over a region appreciably greater than R, the distortional stress being presumably somewhat short of the breaking strength S over a substantial part of the strained region. Further, it seems unlikely that the order of q would be as small as unity or less; for the Long Beach earthquake of March 10, 1933, BENIOFF [1951] estimates that the energy dissipated as heat during 20 days of aftershock activity was more than twice the energy released by the principal earthquake in seismic waves. The Long Beach earthquake was, of course, a shallow earthquake, but there appears to be no reason why a deep-focus earthquake should have an appreciably less value of q.

Conclusions--These considerations lead to the suggestion that either the energies of large earthquakes as calculated from the Gutenberg-Richter magnitude formula may indeed be too great by a factor somewhat greater than 10, or else that the fracture-resisting strength of the material near foci at a depth of 600 km may be at least several times greater than the above suggested value of 100 kg/cm^2.

The first of these alternatives is compatible with what Gutenberg and Richter state on the reliability of the formula (7), but would imply that replacement of the number 12 in the formula by a number less than 11 would give better values of E for large earthquakes. The second alternative is compatible with one school of thought on the question of the strength of the Earth's mantle.

A further inference may be drawn from (6). The rigidity μ increases from about 0.4×10^{12} dynes/cm^2 in the crustal layers to 1.5×10^{12} dynes/cm^2 at a depth of 700 km [BULLEN, 1940]; the incompressibility k increases in about the same ratio. Gutenberg [COLLOQUIUM, 1951] has stated that the energy E in the greatest deep earthquake is about one-tenth that in the greatest shallow earthquakes. It follows from (6) that if q and R may be assumed to be the same in the greatest earthquakes irrespective of focal depth, then the fracture-resisting strength of the material in the vicinity of deep foci is not less than about half that of the materials of the crustal layers. If we assume only that q is constant, then (6) implies that the value of S^2R for the greatest deep earthquakes is at least about 30 pct of the value for the greatest shallow earthquakes. The suggestion arises, in fact, that the reduced energy of deep earthquakes, as recorded by Gutenberg above, may be in considerable measure due to the increases in the elastic parameters with increase of depth in the Earth's mantle; for a given stress distribution, (5) shows that the distortional strain energy is inversely proportional to μ.

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FAULTS AND VOLCANOES

W. Werenskiold

Remarkably often faults in the Earth's crust are accompanied by volcanoes and lava flows, and that on the uplifted flank. Thus, extensive lava flows follow the east side of the great Syrian-African depression. I may be permitted to suggest an explanation of this fact.

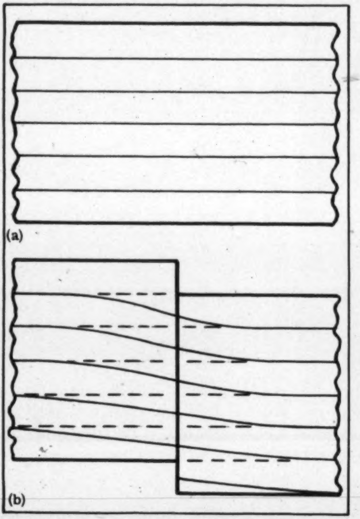

Fig. 1--Vertical section through the Earth's crust; (a) undisturbed; isobars and isotherms are horizontal; (b) the crust has been dislocated through a vertical fault; the isotherms will remain horizontal for a long time, but the isobars will be disturbed, and below the uplifted flank the pressure will be lowered

The matter in the Earth's crust behaves like a rigid body; the temperature and the pressure both rise towards the interior, but are so adjusted that no melting occurs except in special cases. It happens that part of the matter passes into a liquid state, called magma, and this again may rise to the surface, pouring out lava flows. Obviously, the actual temperature down in the Earth's crust cannot be far from the melting point; if the pressure is reduced in some way or other, the solid matter may melt.

A vertical section through an undisturbed part of the Earth's crust will show sets of horizontal isobars and isotherms, so arranged that the matter remains solid, with both pressure and temperature increasing with the depth (see Fig. 1).

Now, let the crust be cut through by a vertical fault, one side sinking, the other rising, relatively. The temperature will remain constant for a long time, but the pressure must be adjusted to the new conditions. The pressure gradient cannot be infinitely great in the semiplastic masses; the isobars must be continuous curves without sudden jumps or angles, and at a distance away from the fault they must remain horizontal. The previously existing balance between temperature and pressure will be disturbed. In a strip below the uplifted flank the pressure will be lowered, and in some cases so much that the solid matter will pass into a liquid state; the magma is forced upwards, issuing at the surface as lava flows. One objection might be made: that a great amount of heat would be necessary in order to melt the solid rock. If, however, the matter is in a glassy state, this process should not require any extra supply of energy.

In this way it seems to be possible to explain the occurrence of volcanic phenomena along the uplifted flank of a fault.

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GEODETIC WORK IN MEXICO FROM MAY, 1950, TO APRIL, 1951

Manuel Medina Peralta

(Translated by F. L. Culley)

Geodetic triangulation--During the year 1950, measurement of the arc along the 101st meridian between latitudes 20° and 30°N was completed. The following geodetic stations were established on this arc during this period: Frailes, Reposa, Salto Colorado, Cerro Grande, Ojito de las Vacas, San Nicolas, Cerritos, Mesa Redonda, Camisa, and Nieves.

The Wild T-3 theodolite was used for observations with 16 circle settings in both positions of the telescope. The mean error of triangle closure was ± 1.20 seconds, and the linear closure of this arc between parallels of 20° and 26° was as follows:

Starting side, Guantes-Culiacan - - - - - log length = 4.4932254
Closing side, Dionisio-Fraile - - - - - - log length = 4.8168496
The same from the triangulation of the 26° parallel = 4.8168424
Difference 0.0000072

which represents an error of 1/70,000.

The part of this arc included between the side Dioniso-Fraile and the side Barrote del 31-Barreta was included in the information presented in 1950. The last side mentioned formed part of the connecting figure with the triangulation of the U. S. Coast and Geodetic Survey.

The triangulation of the State of Oaxaca with that of Chiapas formed an extension in the east-west direction from the 98th meridian destined to connect the triangulation of Mexico with that of Central America. Great difficulties have been experienced in the field in developing the arc included in the State of Oaxaca because of the nature of the terrain and the rarely favorable atmospheric conditions. Generally, in regions of this type, modern elements of radio and aviation are introduced to reduce the time and personnel. The following geodetic stations were established: Flores, Tenango, Guingola, Tecuani, Huilotepec, Gualaguti, Potrero, Tolostoc, Pelon, Palmarillo, and Cienega.

The angles were measured with a Wild T-3 theodolite with a minimum of 16 circle settings. The mean error of triangle closure was ± 0.55 second, and the result of the triangulation computation up to the Tehauntepec base was as follows:

Tehuantepec base (measured) - - - log length = 3.7710748
Tehuantepec base (computed) - - - log length = 3.7710896
Difference 0.0000148

which represents an error of 1/30,000.

Geodetic astronomy--This Office recently acquired a Wild T-4 astronomical theodolite hoping to intensify its Laplace determinations. It is believed that the principal advantage of this instrument lies in its double use as an altazimuth instrument for determination of azimuth and as a zenith astronomic telescope for determination of latitude and longitude. However, attentive to a resolution adopted in the Fifth General Assembly of the Pan American Institute of Geography and History on the advantage of making a previous study of the instruments of new manufacture, it has proceeded to establish an astronomic station with this instrument in order to compare it with the results which the Repsold and Sohn apparatus of the reversible type provides.

Precise leveling--The geodetic levelings made across the Valley of Mexico, starting in 1938, have shown plainly the gradual and certain accelerated sinking of the ground on which Mexico City is located, especially in the central part. Given the importance of this fact, specialists in this subject have made studies based on leveling periodically established by this Office.

The final results confirm that one of our leveling bench marks located on the Monument to Carlos IV in the Paseo de la Reforma has sunk in the last 29 months at the rate of four centimeters per month.

In the last months of 1950, new leveling was run between the towns of Taxco and Iguala of the State of Guerrero, in order to replace some bench marks that had been destroyed. The leveling, which was performed with a Wild N III level of great precision, extended 34 kilometers.

Study of some Invar wires to be used for base measurements--With the purpose of measuring Tehuantepec base, a new comparison of the wires was made as a practice measurement. This comparison was made on the wall marks existing on the Comparador de Longimetros, and they showed little difference with results of the earlier comparison. In order to justify these, a new distance was established between the 0-24 m master marks fastened in the foot of the Comparador. This new measurement was made using the four-meter standard of Invar which the Office owns, finding the value of the distance between the 0-24 m marks different from the earlier measurement by 0.000074 m. This small difference may be explained as due to two causes: (1) by change of the molecular structure of the standard, or (2) by an effective change in the distance between the marks of the foot due to the frequent seismic shaking to which the subsoil of Mexico City and especially of Tacubaya is subject. In order to explain this, we are awaiting from the Inter-American Geodetic Survey a shipment of various Invar tapes which were recently compared to use as rectifying standards, meanwhile returning our four-meter standard to Washington for restandardization.

Gravity--A new determination of the periods of oscillation was established for pendulums 5, 10, and 11 on the Gravimetric Pillar 2 of this Office for the purpose of beginning a new circuit of field observations, possibly in the northwest region of the country.

Cartography--In regard to new publication of maps and charts, we can only report the completion of 22 sheets of the map of the Republic on the scale of 1:500,000 lying between the 15° and 22° parallels of latitude which the Coordinating Committee of the Map of the Republic accomplished with the cooperation of this Office.

Oficina de Geografia,
Tacubaya, D. F., Mexico

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GEODETIC WORK IN MEXICO FROM MAY, 1951, TO MARCH, 1952

Manuel Medina Peralta

(Translated by F. L. Culley)

Triangulation--Special attention has been given to the completion of the observations connected with the tieing-in of Mexican-Central America triangulation across the frontier between this country and Guatemala. Figure 1 shows the progress of the operations up to the first days of April, 1952. The unbroken lines represent sides already determined, and the dotted lines are sides in progress in April, 1952. This triangulation starts from the Yucuyacua-Gavilán side of the triangulation along the 98° meridian and extends to the Tacaná-Monte Limar side of the Guatemalan triangulation. It consists of 17 figures and 48 stations, of which 37 have been completed and 11 are being observed.

There are two bases already measured within this net: one at Tehuantepec, six km long, and the other at Tapachula, 14 km long. Two Laplace stations have been determined, the first at the Monte Albán station, close to the Yucuyacua-Gavilán side, and the second in the extreme north of the Tehuantepec base. The angle measurements of this triangulation have been made with Wild T-3 theodolites, with 16 circle settings in each direction.

The average closing error of the 36 triangles observed is 0.63 second, the maximum and minimum closing errors being, respectively, 2.85 and 0.01 second. The Tehuantepec base, calculated through the triangulation pattern, differs from the measured base by 0.201 m, which represents a relative error of 1:29,368.

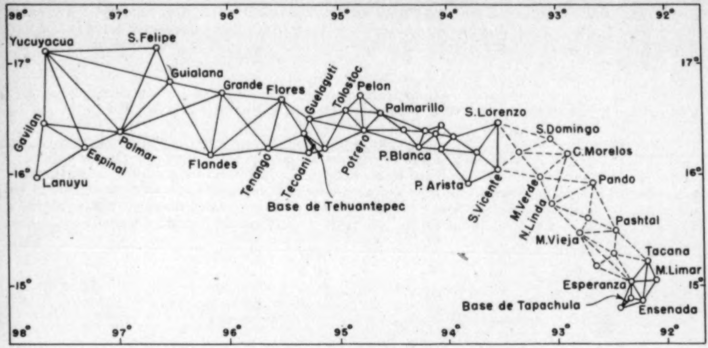
98°
97°
96°
95°
94°
93°
92°
17°
16°
15°
Yucuyacua
S.Felipe
Guialana
Grande
Flores
Guelaguti
Tolostoc
Pelon
Palmarillo
S.Lorenzo
S.Domingo
C.Morelos
Pando
Gavilan
Palmar
Espinal
Lanuyu
Flandes
Tenango
Tecoani
Potrero
P.Blanca
P. Arista
S.Vicente
M.Verde
N.Linda
Pashtal
M.Vieja
Tacana
M.Limar
Esperanza
Base de Tehuantepec
Base de Tapachula
Ensenada

Fig. 1--Oaxaca-Chiapas triangulation

The following operations have been initiated for the purpose of strengthening the rigidity of the geodetic loop formed by the triangulation arcs measured along the 98°, 101°, and 103° meridians and the 19° 30′ and 26° N parallels, from which the triangulation of the States of Oaxaca and Chiapas starts:

(1) Measurement of an arc along the 23° parallel to connect the 98°, 101°, and 103° meridian triangulations.

(2) Measurement of new geodetic bases on the 101° and 103° meridians.

(3) Determination of new Laplace stations.

The triangulation proposed along the 23° parallel (see Fig. 2) is composed of four quadrilaterals, of which the following stations have been observed: Sabino, Jabali, Cantera, and Cerritos.

Wild T-3 theodolites were used in reading the angles of these stations, with 16 repeats for each line of sight.

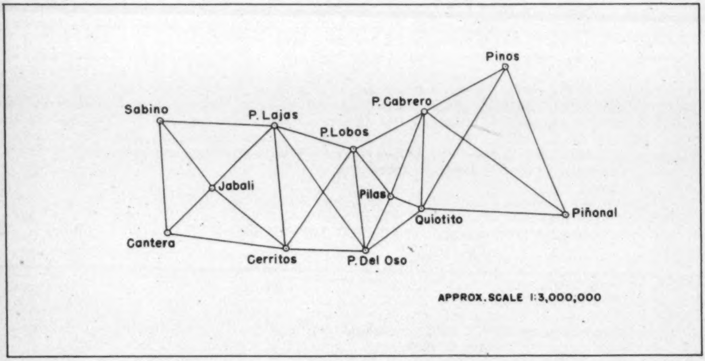
Pinos
Sabino
P. Lajas
P. Cabrero
P.Lobos
Jabali
Pilas
Quiotito
Piñonal
Cantera
Cerritos
P. Del Oso
APPROX. SCALE 1:3,000,000

Fig. 2--Triangulation along the 23° parallel North

Geodetic bases--Two new base lines were located on the triangulation of the 101° and 103° meridians. The second of these, called Base de Cedros, was measured in January, 1952, using Invar wires 25, 26, 32, 33, and 34, each being 24 m long. This base, currently being calculated, is nine km long and is tied directly to the Julián-Carpintero side of the triangulation along the 103° meridian.

For that purpose, angle observations were made at the four following stations: Carpintero, extreme south end of the Cedros base, extreme north end of the Cedros base, and Julián.

Since the wires used in the measurement of this base have not been calibrated recently, and since it is known that such wires undergo certain small changes in length with the passage of time, a 50-m Invar tape, for which there is a recent calibration certificate from the National Bureau of Standards in Washington, was used as standard and a small auxiliary base, 600 m long, was measured with that tape and with each one of the above-mentioned wires, with the following values being obtained at 15°C temperature, ten kg tension, the ends being supported:

Wire 25	24 m + 0.511 mm
Wire 26	24 m - 1.860 mm
Wire 32	24 m + 0.388 mm
Wire 33	24 m + 3.215 mm
Wire 34	24 m - 0.074 mm

With the exception of wire 34, which according to our records has changed notably since the prior standardization, the results obtained for the other wires guarantee their lengths within the requisite accuracy.

Geodetic astronomy--Observations for latitude, longitude, and azimuth were made at the following stations: Primales of the 101° meridian triangulation, and in the extreme north end of the Bermejillo Base, in the 26° parallel chain. Both stations have the characteristics of Laplace stations.

The observations were made with a Wild T-4 astronomic theodolite, being used for the first time in this Office for this class of work. In order to make a comparative study of this instrument with the Repsold Zenithal (Bamberg type), time determinations were made with both instruments at the Primales station.

The geographic coordinates of Palma de Colonche in the State of Aguascalientes were determined, using expeditious methods, for immediate cartographic use.

Gravity measurements--The University of Wisconsin, in combination with the Geophysical Institute of the National University of Mexico and this Office of Geography, made two gravimetric surveys in this country. The first included observations with a Worden gravimeter at points situated along the principal highways (approximately one station every 20 km); and the second consisted of base stations at three points, using the quartz pendulum equipment of the Gulf Research and Development Co. The calculation of these positions has not yet been completed.

Precise leveling--Precise leveling across the Isthmus of Tehuantepec has been started along the highway between Coatzacoalcos, Veracruz, and Salina Cruz, Oaxaca. Two parties are operating simultaneously along that line from opposite directions, starting from the bench marks established near a tide gage in Coatzacoalcos on the coast of the Gulf of Mexico and the gage which is now being set up at Salina Cruz on the Pacific Ocean coast. Wild N-III levels and Invar rods of the same manufacture are being used in this operation.

Another precise leveling operation has also been started between Tapachula, Chiapas, and Tehuantepec, Oaxaca, along the railroad which links the two cities. This leveling will be connected with the level net of Guatemala and Central America across the frontier at Talisman, Chiapas.

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REPORT OF THE STANDING COMMITTEE ON PROBLEMS OF THE UPPER ATMOSPHERE, 1951-1952

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The year 1951-1952 has been a significant one in the history of upper-atmosphere research, not because of any single revelation but because a large number of important research projects started shortly after the end of World War II are reaching fruition and being reported. The great activity in this broad field makes it impossible to record all the events of the past year, so this report must merely serve as a brief and very general review. The extensive list of references will make it possible for anyone interested to obtain more details.

Review of methods for observing the upper atmosphere--At the final meeting of the NACA Upper-Atmosphere Subcommittee in 1951, the chart shown in Figure 1 was drawn up, summarizing the various methods that have been devised for sounding the upper atmosphere and giving the heights to which they each apply.

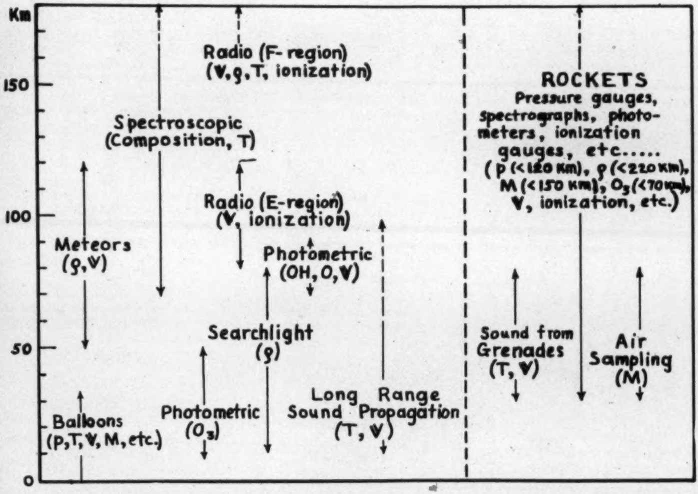

Fig. 1--Approximate ranges of altitude for various upper-air observation techniques; symbols are: ρ, density; p, pressure; T, temperature; V, wind; M, molecular weight; some of the ranges shown may be extended eventually

Results of rocket soundings--Nearly all German V-2's have now been consumed. Aerobees are now the most widely used upper-atmospheric rockets. Several successful flights of the new Viking have been made. It has reached an altitude of 135 miles with about 450 pounds of apparatus.

A continuing effort is being made to obtain more comprehensive data on atmospheric pressure, temperature, and density at high altitudes. The techniques used include direct pressure-gage measurements, sound ranging on explosions of grenades ejected from the rockets at a series of altitudes, measurements of "Mach angle" of the supersonic shock wave formed at the nose of the rockets, and other measurements whose significance stems from aerodynamic theory [NEWELL, 1951; WHIPPLE, 1952; HAVENS and Others, 1952; FERENCE, in press].

In all, over 14 successful flights from which pressures, densities, or temperatures were measured have taken place. The highest observation was one of density at 219 km, which gave 1×10^{-7} gm/m^3 [HAVENS and BERG, 1952]. Some flights were made at the equator from an aircraft carrier, but most were at White Sands, New Mexico.

Many of the new data have not yet been published in comprehensive form. The members of the Upper-Atmosphere Rocket Research Panel have recently been engaged in preparing a "best" atmosphere up to about 160 km altitude by the weighted synthesis of all available data from rocket flights at White Sands (lat. 33°N, long. 106°W). There is rather impressive agreement among results of independent methods of measurements. The true atmosphere at this locality differs markedly from the tentative standard atmosphere of the Special Subcommittee of the NACA [WARFIELD, 1947]. For example, the temperature maximum at about 50 km is some 265°K, and the temperature minimum at about 80 km is some 190°K. The corresponding values for the NACA standard are 350°K and 240°K, respectively. It is not yet established whether similar discrepancies exist at higher latitudes, but sound-ranging experiments at more northerly latitudes seem to support the atmosphere determined by rockets more closely than the NACA standard. It is hoped that rocket research agencies will turn their efforts to other latitudes. The NACA Special Subcommittee was dissolved in November, 1951, without reaching agreement on modifying the official atmosphere in accordance with new rocket data. It therefore appears that the "legal atmosphere" and the true atmosphere will continue to differ markedly.

The University of Michigan group has continued air sampling to learn the chemical composition of the upper atmosphere. Most measurements have shown no certain change in the relative abundances of the atmospheric gases up to 70 km. However, three samples have shown a significant change in the 60-70 km region [CHACKETT and Others, 1951; JONES and Others, 1951]. The helium-nitrogen ratio was about twice as great as in sea-level air, the neon-nitrogen was about 20 pct greater, and the argon-nitrogen ratio was about ten per cent less. These results, internally consistent, constitute the first clear evidence for gravitational sedimentation of atmospheric gases. It is of concern that the results of analysis of these three samples are in marked disagreement with the general body of previous data. This may be due to improved techniques or to peculiar atmospheric circumstances on the day of sampling.

New measurements of ozone distribution have been reported [JOHNSON and Others, 1951; VAN ALLEN and HOPFIELD, 1952]. The latter authors have measured the integral amount above successive levels from 20 to 65 km with a photomultiplier-quartz-spectrograph arrangement carried in an Aerobee rocket. Sample results are shown in Table 1.

Table 1--Sample of the ozone data

Height H	Total ozone
km	cm^a
20	0.082
25	0.052
30	0.033
35	0.020
40	0.011
45	0.0049
50	0.0015
55	0.00036
60	0.000080

[a] Normal temperature and pressure vertically above H.

Ion and electron densities have been observed by radio waves to and from the rocket, by electrometers set into the skin of the rocket, and by probe-and-ring conductivity measurements. When these observations are reported, they should afford an important check on ionospheric-recorder techniques [SEDDON, 1952].

The intensity of the Sun's radiation in the ultra-violet and soft X-ray region has been observed. These radiations, mostly absorbed between 30 and 90 km, show the Sun to radiate with an effective temperature of less than 5000°K in the near ultra-violet, but in the far ultra-violet and soft X-ray region the intensity may correspond to a solar temperature of much more than 6000°K, though it appears that the intensity may also vary considerably [TOUSEY and Others, 1951].

Twenty-seven values of winds at 30 to 50 km have been observed by the deflection of sound waves from grenades ejected from the rocket [WEISNER, in press]. These winds appear to be generally easterly in summer and westerly in autumn and winter. A single value of the wind at 200 km has been obtained by an aerodynamic method [HAVENS and SPITZ, 1952].

Daytime airglow and presence of clouds at around 80 km have been observed by photometers in rockets. The daytime airglow is generally constant from 40 to 130 km and is reported to be much larger than predicted [MILEY, 1952].

Ionospheric sounding by radio methods--(See also the URSI report [BOOKER, 1952].) The Carnegie Institution of Washington and the Central Radio Propagation Laboratory (CRPL) of the National Bureau of Standards have been studying the fine structure and motions in the ionosphere. The CRPL has determined ionospheric winds from fading patterns of pulsed 2.3-Mc waves reflected from the ionosphere and received by a three-receiver array spaced about 200 m apart [SALZBERG and GREENSTONE, 1951]. These winds exhibit diurnal characteristics which change with season. The Carnegie Institution studies of local changes in ionospheric structure were made with a triplet of fast-sweeping ionospheric recorders spaced a greater distance apart. Marked differences in ionospheric behavior have been noticed at locations separated by only 30 miles.

The CRPL, using a high-power pulse transmitter whose frequency may be varied between 30 and 300 kc, has, among other things, established a strong correlation between geomagnetic and low-frequency ionospheric disturbances [WATTS and BROWN, 1951; McNISH, 1952]. In England the same effect has been studied by comparing sky and ground wave signals from the Rugby transmitter at 16 kc, the phase difference being very sensitive to the height of the bottom of the D-layer. Solar flares were observed in a number of cases to result in an immediate lowering of this height [BRACEWELL and STRAKER, 1949].

Relationships between auroral activity and sporadic-E echoes have attracted attention, and during March, 1951, the CRPL station at Point Barrow, Alaska, obtained some 400 visual observations of aurora simultaneously with regular ionospheric soundings. Results indicate that quiet auroras, 45° or higher above the horizon, are correlated with sporadic-E echoes. Also, active auroral displays usually coincide with a sharp increase in radio energy absorption [KNECHT, 1952].

Sound propagation studies--Results since those previously reported [KELLOGG and Others, 1951] were obtained during the winter of 1950 at the Canal Zone, Hawaii, Bermuda, and Florida [CRARY, 1952]. There is general confirmation of previous observations and an indication that there may be differences in the stratospheric temperatures and winds between continental and oceanic stations. Most of these winter observations show southerly components of the wind.

Meteors--(See previous Committee report [KELLOGG and Others, 1951].) The Harvard group is now using a pair of super-Schmidt cameras in New Mexico [WHIPPLE, 1952]. The Stanford group is still actively studying meteor trains by radio methods, and has gathered new data on winds and drifts at meteor altitudes [MANNING and PETERSON, 1951; MANNING, VILLARD, and PETERSON, 1950, 1953].

Airglow and aurora--Two international colloquia included papers on optical studies of night airglow and aurora and related problems, which form a comprehensive review of this field [ONTARIO COLLOQUIUM, 1951; LIEGE COLLOQUIUM, 1952; HUNAERTS, 1951]. Recently observations have been published dealing with the absolute intensity of the sodium D line emission in the airglow [ROACH and PETTIT, 1951], of the OI line of oxygen at 5577 A and its variation with time and space, indicating motions of emission patterns across the sky [DAVIS, 1951], and several dealing with emission from the aurora [GARTLEIN, 1950; MEINEL, 1951b; NICOLET and DOGNIAUX, 1950]. Recent improvements in photometric techniques make it possible to map the emission patterns of the airglow and aurora over the whole sky within a few minutes, and detailed studies of these patterns at Cactus Peak and elsewhere are expected to throw new light on atmospheric motions in the layers of emission.

Identification of lines and bands in the airglow spectrum is fairly complete, but there are still many unresolved problems concerning the processes that give rise to the various emissions, particularly those in the blue below 5000 A and in the near infrared. One attempt to extend airglow identification toward short wavelengths [HUNAERTS and NICOLET, 1950] tries to explain the X_1 and X_2 bands of Rayleigh (two bands around 4435 A and 4210 A, first explained as Vegard-Kaplan bands by Kaplan), presenting evidence that they are really the OH bands 9-1 and 8-0 and suggesting that other bands such as (10-1) at 4045 A, (10-2) at 4690 A, and (11-3) at 5002 A may also be present.

Observation by KRASSOVSKY [1949, 1950], who used a prismatic spectrograph and a Cs-O-Ag electron image converter, of night airglow spectra in the near infrared between 8000 A and 11,000 A has been discussed by J. DUFAY [1951]. Dufay suggests that the emission reported by Krassovsky at 9976 A could be due in part to the (0,2) O_2 band of the atmospheric system. This observation, surprisingly, tends to confirm the fact that the level v' = 0 of the forbidden $^1\Sigma \rightarrow {}^3\Sigma$ system of O_2 is exclusively excited. There are several suggestions for a secondary mechanism that could remove the molecules from states for which v' > 0 to the v' = 0 level. One by Bates is

$$O_2\,{}^1\Sigma\ (v' > 0) + O_2\,{}^3\Sigma\ (v'' = 0) \rightarrow O_2\,{}^3\Sigma\ (v'' > 0) + O_2\,{}^1\Sigma\ (v' = 0)$$

Objections have been raised to this suggestion by Meinel, on the grounds that this exchange process does not work for the other electronic bands in the night airglow spectrum; for example, the Herzberg and Vegard-Kaplan bands in the night airglow originate on v' > 0.

MEINEL [1951b] has called attention to the great variability of the Kaplan-Meinel band of O_2 in the night airglow. Regardless of the ultimate explanation of its mechanism of excitation, whether this is a two-body radiative recombination or a three-body collision, it will be important to continue to observe and to explain this variability.

BRANSCOMB [1951], studying the atmospheric oxygen bands in discharges, has found that, because of the high probability of recombination on metal surfaces, an electrodeless discharge is propitious for afterglow production. This supports the hypothesis that the oxygen afterglow is a recombination involving three-body collisions. Branscomb computed the rotational temperature of the afterglow from the profile of the unresolved (O,O) band and obtained a temperature of about 310°K, which was approximately room temperature. He concluded that the excited O_2 molecules in the afterglow appear to attain thermal equilibrium before radiating, as would be expected from their low transition probability and the moderately high pressure. Since Meinel and J. Dufay used the rotational profile of the (O,1) band of O_2 to measure the temperature of the upper atmosphere, Branscomb cites the normal behavior of the atmospheric bands in the discharge and in the afterglow in substantiation of the interpretations of Meinel and Dufay.

KASH [1951] has provided an excellent method for study of decay of afterglows. It is proposed to apply this method to the study of the decay of the v' = 0 bands of the O_2 atmospheric system and to try in this way to distinguish between three-body collision and a more complex process made up of three-body collisions followed by some kind of secondary mechanism, for example, the one suggested by Bates.

Observation at the end of twilight and during the first hours of the night of the forbidden ^2D - ^4S line of NI has been reported by several writers, among whom are COURTES [1950], NICOLET and PASTIELS [1952], and M. M. DUFAY [1951]. The proposed mechanism is absorption of solar radiation of wavelength 3466 A, which brings the atom to the ^2P state, the subsequent radiation ^2P - ^2D (10,406 A), bringing the atoms to the ^2D level. The short (two-second) lifetime of ^2P and the long (> eight hours) lifetime of ^2D account for the observations. Nicolet and Pastiels suggest the permanent presence of atomic nitrogen above 150 to 200 km and explain the presence of N_2^+ bands in the twilight airglow at 100 km by X-ray ionization and in the auroral rays by the recombination process

$$N + N^+ \rightarrow N_2^+ + hv$$

BATES [1951a] continues his theoretical studies of the rate at which free atoms form molecules by radiative association. He has published a paper in which a revised formula for the coefficient expressing the rate is derived. He has applied these to both astrophysical and geophysical problems.

In order to test the hypothesis that auroras are created by deceleration of high-energy protons penetrating the atmosphere [GARTLEIN, 1950; MEINEL, 1950b], MEINEL and FAN [1952] have studied the spectrum produced by firing protons at about 230 kev into a sample of air at low pressure. The resulting spectrum agreed almost exactly with a spectrum of an aurora obtained at College, Alaska, by BARBIER and WILLIAMS [1950]. Although electrical discharges in the laboratory have never produced a complete auroral spectrum, the authors are careful to point out that their result does not rule out the possibility that auroras may be formed by deceleration of other high-energy particles beside protons and already plan to study the spectrum from an electron beam in air.

General theoretical studies--Among theoretical studies of properties of the upper atmosphere, three treatments of radiative budget and temperatures of the upper atmosphere are particularly interesting.

BATES [1951b] discusses the heat balance in the ionosphere and finds that conduction is the dominant factor in determining loss of energy in the F-region, as previously suggested by SPITZER [1949]. Several alternative processes are investigated for the gain of energy, and it is pointed out that the mechanisms for loss are so effective that none of the usually postulated sources of energy is sufficient to give a balance. Attention is drawn to the possibility that the original estimate of the contribution from ionizing photons may be much too small.

GERSON [1951] critically examines and discusses the theory and observational results of a large number of ionospheric temperature determinations, concluding that temperatures below 400 km are generally somewhat lower than usually estimated [GRIMMINGER, 1948] and that diurnal changes are small. The latter conclusion is partly based on radiative transfer and conduction considerations, and it is admitted that the factors involved in the ionospheric heat budget are very incompletely understood.

JOHNSON [1952] treats the radiative balance in the stratosphere, using direct measurements of ozone distribution by rockets (see above) and of the distribution of solar ultra-violet. The heat absorbed by ozone in the Chappuis, Huggins, and Hartley bands has been calculated over the altitude range 20 to 70 km. Assuming quasi-steady conditions, it was determined that the diurnal temperature change has a maximum value of 5.3°C at 48 km, and falls to 1°C at 31 km and 70 km. The times of maximum and minimum temperatures also varied with altitude.

A comprehensive review of upper-atmosphere data and some of the theoretical considerations of the physical characteristics has been published by NICOLET and MANGE [1952]. An effort is made to determine the essential physical characteristics of the high atmosphere, followed by treatments of the oxygen distribution (photochemical equilibrium) in the 80- to 100-km region and of molecular diffusion above 160 km.

The mean circulation in the stratosphere (and lower ionosphere) and the pressure and temperature distribution in the meridional plane have been set forth in papers by KELLOGG and SCHILLING [1951] and WAN-CHENG CHIU [1951]. A paper in preparation brings the former work up to date and cites a number of new observations that tend to confirm the hypothesis of a pole-to-pole flow of air in the stratosphere from the summer to the winter hemisphere, accompanied by east winds in the summer hemisphere, west winds in the winter hemisphere, and a general subsidence in the stratosphere near the winter pole.

Atmospheric-solar relationships--As pointed out in the previous Committee report [KELLOGG and Others, 1951], there is rather good evidence for direct relationships between solar activity and ionospheric conditions. Papers by BODURTHA [1952], CRAIG [1951, 1952], and WEXLER [in press] have extended this atmosphere-Sun coupling to the troposphere. Wexler attempts to show a possible mechanism whereby changes in solar ultra-violet emission could have an effect on sea-level pressure. Craig extends a previous analysis of DUELL and DUELL [1948], which shows a marked correlation between geomagnetic activity and average surface pressure variations, and Bodurtha finds a correlation between rate and frequency of anticyclogenesis over Alaska and northwest Canada and sunspot number. These studies all point to the coupling that must exist between the troposphere and the upper atmosphere, but which is still incompletely understood.

Searchlight soundings--A revival of the technique for determining stratospheric density by means of scattering from a searchlight beam has been reported [ELTERMAN, 1951]. The experiment was conducted in New Mexico by the Air Force, and results show qualitative agreement with the RAND atmosphere [GRIMMINGER, 1948]. In all, eight determinations were made to 61.8 km, and a seasonal trend was noted.

Laboratory studies--Experiments by Meinel, Branscomb, Kash, and others have been described above. Another laboratory study [WEISLER and Others, 1952] treats the absorption spectrum of N_2 in the far ultra-violet between 661 and 796 A. These results permit a better estimate of the level of dissociation of N_2 in the ionosphere, though the intensity of the solar emission in this region is still in doubt. (A continuation of the paper on this last subject by WOOLLEY and ALLEN [1950] is in press.)

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OCEANOGRAPHIC ACTIVITIES OF THE HYDROGRAPHIC OFFICE, 1946-1952

John Lyman

The formation of a Division of Oceanography in the Hydrographic Office was announced by GLOVER [1946], and its early progress was described by BATES and FLEMING [1947]. Work in many phases of oceanography has continued.

Surveys--The two oceanographic survey vessels, USS San Pablo and Rehoboth, were commissioned late in 1948 [AUSTIN, 1951]. Since that time they have made ten cruises, principally in the Atlantic, carrying out a wide variety of measurement programs [ABEL, 1951]. Some of the statistics of the ten cruises are impressive: 206,661 miles steamed; 720 stations occupied; 12,776 bathythermograph slides obtained; 82 cores recovered; 864 days spent at sea.

The seismic survey program, being conducted in collaboration with the Lamont Geological Observatory, has so far embraced 29 stations, and is rapidly yielding information on the structure of the floor of the North Atlantic. Together with the Canadian Naval research vessel New Liskeard, the Woods Hole Oceanographic Institution research vessels Atlantis and Caryn, and the U. S. Fish and Wildlife Service vessel Albatross III, the two vessels participated in Operation CABOT, a two-week multiple-ship survey of the Gulf Stream, in June, 1950. The data collected by the six vessels, together with the observations of the International Ice Patrol vessel Evergreen, which operated in the area to the eastward, have been turned over to Woods Hole Oceanographic Institution for analysis.

The size and versatility of these two vessels make it possible to undertake unusual types of sampling or measurements in addition to the routine serial observations of temperature, salinity, oxygen, and nutrients, the continuous recording of echo soundings, and the sampling of the bottom sediments. Thus the 1000-liter sea-water samples, which yielded the carbon^{14} whose age was recently reported on by Kulp, were obtained by the San Pablo in the eastern North Atlantic from a depth of 1900 to 2900 m; and this type of sampling continues.

Oceanographers have also accompanied the Navy ice-breakers Edisto and Atka in their annual cruises to northern waters, and additional oceanographic data have been obtained in this way from waters where unprotected vessels would have difficulty in operating [BATES and LILL, 1950].

Nearer home, a program of oceanographic surveying in the coastal waters of the United States has been inaugurated, in cooperation with the U. S. Coast and Geodetic Survey, the Office of Naval Research, and various scientific institutions, including Woods Hole Oceanographic Institution; the Universities of Rhode Island, Delaware, California, and Washington; Cornell and Rutgers Universities; and the Chesapeake Bay Institute.

Data collection--Supplementing regularly-scheduled survey operations, the Hydrographic Office makes use of several types of data collected more or less routinely by vessels engaged in other pursuits. For example, the navigating officers of hundreds of merchant vessels of all flags twice daily compare their dead-reckoning positions with their astronomical fixes at morning and evening twilight, and the differences, after all other errors are carefully eliminated, are reported to the Hydrographic Office as current. On the forms for this purpose, which are furnished by the Hydrographic Office, they also record sea-surface temperatures and sea and swell conditions, and these reports, compiled statistically, serve as the basis for our current, surface temperature, and sea and swell atlases.

A modification of this technique, first employed on the Woods Hole vessel Atlantis, is now being used to study the Gulf Stream between Florida Straits and Cape Hatteras. Here the fixes are obtained hourly by loran on a group of tankers on the regular run to Gulf oil ports, and the short interval between fixes -- 15 miles or so, during which the influence of the Gulf Stream may reveal itself in a five- or six-mile offset from the dead-reckoning position -- makes it possible to obtain a much finer-grained pattern. The first year's study [U. S. HYDROGRAPHIC OFFICE, 1952] has yielded recommended summer and winter northbound routes which may cut three hours off the steaming time of a 15-knot vessel by taking advantage of the maximum current velocities.

Still another routine collection program is that of bathythermograph prints. In collaboration with the Scripps Institution of Oceanography, the Woods Hole Oceanographic Institution, and the Office of Naval Research, the Hydrographic Office maintains facilities for enlarging the rather small and fragile record of temperature against depth obtained by this instrument into a permanent and practically indestructible photographic print, with the temperature and depth scales superimposed. Naval vessels regularly send their collections of slides, carefully annotated; and fleet commanders are helpful in routing bathythermograph-equipped vessels through waters previously unsampled. The Ocean Station Vessels of the Coast Guard also cooperate in obtaining bathythermograph data, as well as in running lines of soundings on their way to and from stations. The nearly continuous series of bathythermograms from the Ocean Stations, some of which have been occupied regularly for over five years, are among the best available data on the climatology of the ocean's surface.

A growing number of research institutions both in America and abroad are availing themselves of the bathythermograph processing facilities of the Hydrographic Office, with the result that the geographically-arranged master file of prints now contains more than 410,000 individual observations.

Data processing--One of the prime interests of the Hydrographic Office has been to diminish the work necessary in reducing the raw data collected by its survey ships to the standard depths and computed values in which oceanographic observations are customarily published. To this end, various slide rules and nomograms have been constructed, notably the specific-volume anomaly and current nomograms described by CALLAWAY [1951], but more recently emphasis has been placed on machine methods. We now have the IBM card-programmed computer wired for computation of sigma-t from temperature and salinity, and for the computation and integration of dynamic heights from temperature, salinity, and the interpolated depths of an oceanographic station. As in the case of bathythermograph processing, these facilities are available to any oceanographic institution desiring to make use of them, subject, of course, to the priority of naval requirements.

In return, the Hydrographic Office is enabled to make use of such data long before they might otherwise be published in the ordinary course of events. Ever since being faced with the problem of storing the vast amount of unpublished Japanese oceanographic data (30,575 stations) acquired in 1945 and 1946, the Hydrographic Office has had under study the most expeditious way of putting oceanographic data on punch cards. This technique is not exactly a new one to us -- the Hydrographic Office began experimenting with such a means of handling oceanic data in 1894, only seven years after Herman Hollerith invented the system, and the current, sea-surface temperature, and sea and swell data already mentioned have been handled in this way since 1932. Accordingly, a standard layout was devised, the Japanese data were punched in 1949 and 1950, yielding a total of 452,000 cards, and subsequent additions from other waters have raised the total to over one million. In addition to these cards of serial oceanographic observations, the Hydrographic Office now has on hand 3,100,000 cards of surface ocean weather observations from the Deutsche Seewarte deck, and 2,500,000 cards representing surface current, temperature, and sea and swell.

Bibliographic work--A comprehensive card file of oceanographic subjects and authors, begun during World War II, has been maintained and is added to daily. Recently all the back issues of Annalen der Hydrographie und Maritimen Meteorologie, Annales Hydrographiques, and Annali Idrografico were indexed, and the cards were duplicated and sets distributed to various agencies expressing a need for them.

Publications--Since 1946 the Hydrographic Office has issued the following oceanographic publications:

H.O. Pub. No. 238, References on the physical oceanography of the western Pacific Ocean, 1946.
H.O. Pub. No. 570, Atlas of surface currents, North Pacific Ocean, 1947.
H.O. Pub. No. 601, Wind, sea, and swell; theory of relations for forecasting, by H. U. SVERDRUP and W. H. MUNK, 1947.
H.O. Pub. No. 602, Wind waves at sea, breakers and surf, by H. B. BIGELOW and W. T. EDMONDSON, 1947.
H.O. Pub. No. 604, Techniques for forecasting wind waves and swell, 1951.
H.O. Pub. No. 605, Graphical construction of wave refraction diagrams, by M. P. O'BRIEN and J. W. JOHNSON, 1948.
H.O. Pub. No. 606, Observers' manual; 606b, Sonic soundings, 1950; 606c, Bathythermograph observations, 1951; 606e, Sea and swell observations, 1950.
H.O. Pub. No. 609, Functional glossary of ice terminology, 1952.
H.O. Pub. No. 614, Processing oceanographic data, by E. C. LA FOND, 1951.
H.O. Pub. No. 615, Tables for sea-water density, 1952.

In addition, following the lead of various foreign hydrographic offices, a chapter on the oceanography of each coast is being added to the Sailing Directions, as they are rewritten, and several chapters on oceanography are planned for the revision of Bowditch (H.O. Pub. No. 9, The American practical navigator).

Two training films, one showing the operation of a bathythermograph and the other various procedures in occupying an oceanographic station, have also been prepared and are available on loan to interested activities.

Other work--Studies recently reported on by personnel of the Hydrographic Office in the field of oceanography include such topics as sea and swell [BATES, 1947; BATES, 1949; FLEMING and BATES, 1951; and MacDOUGAL, 1951], the scattering layer [LYMAN, 1948a], discolored water [HAYES and AUSTIN, 1951], pressure-pattern navigation [LYMAN, 1948b), underwater sound [U. S. HYDROGRAPHIC OFFICE, 1947], the preparation of special symbols [BATES and KOLB, 1952], and the physical characteristics of environmental regions [FLEMING, 1948, and ELLIOTT, 1951].

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REPORT OF THE COMMITTEE ON SNOW, 1950-1951

Walter U. Garstka, Chairman

1951	1952	1953
Wayne D. Criddle	E. G. Dunford	Henri Bader
Forrest L. Rhodes	James C. Marr	George O. Guesmer
Vincent J. Schaefer	Walter T. Wilson	Duart A. MacLean

The report of the Committee on Snow consists of a survey of current activities dealing with research on snow compiled by members of the Committee in correspondence with workers listed below. The character of the reports and the comprehensiveness of the subjects attest to the virility of research on snow.

Henri Bader and George O. Guesmer (Snow, Ice, and Permafrost Research Establishment, Wilmette, Ill.)--(a) The organization is preparing a research program and facility survey by contract with the University of Minnesota and with Purdue University. (b) Field tests of snow-compacting equipment are being conducted in Ontario in cooperation with the Engineering Research and Development Laboratories. (c) Snow and ice-removal techniques will be studied by SIPRE and ERDL. (d) Basic research on snow classification and compaction is being done by the University of Minnesota. Metamorphosis of snow is being studied by SIPRE at the Central Sierra Snow Laboratory, Soda Springs, California. (e) Basic research on mechanics and crystallinity of ice is being done at the University of Michigan; deformation of single ice crystals is being studied by the University of California at Los Angeles. (f) Basic research on frozen ground and permafrost is being conducted for SIPRE by the Soils, Foundation, and Frost Effects Laboratory, New England Division, Corps of Engineers. The entire field of the effects of seasonal frost action on all types of structures is also under study by this Laboratory. (g) The Permafrost Division, St. Paul District, Corps of Engineers, is studying all phases of permafrost in the field.

M. E. Baudendistel (Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Mont.)--All of the snow studies in this listing are directed towards determining hydrologic factors for use in the analysis of flood-control survey of field data. Activities at Priest River include: (a) observations of the influence of altitude and aspect on snow accumulation and melt at three pairs of watersheds in timber; (b) measurements on "transects" on cleared strips extending from ridge top to ridge top across Benton Creek valley, transect altitudes ranging from 3250 to 4060 ft above sea level; (c) observations of influence of forest cover on snow accumulation and melt at lower, middle, and upper slope positions along the open transects and in the adjacent timber.

The hydrology of a 960-acre, heavily timbered watershed is also being studied, within which precipitation is being measured with 16 winter and 25 summer gages, and 15 snow courses. Air temperatures and wind velocities are taken at three locations. Electrical soil-moisture and temperature installations are maintained at three locations. Records began in the fall of 1949, except for two precipitation gages and stream flow, which began 12 years ago.

Wm. L. D. Bottorf (Technical Director, Cooperative Snow Investigations, Corps of Engineers) and Walter T. Wilson (Chief, Weather Bureau Analysis Unit, Cooperative Snow Investigations)--The initial five-year period of this joint program is summarized in Progress Report, 1945-1950, Cooperative Snow Investigations, released by the South Pacific Division office of the Corps of Engineers. Operations at the Central Sierra and Upper Columbia Laboratories have been curtailed somewhat. Operations are continuing without curtailment at the Willamette Basin Snow Laboratory. Analytical program has been accelerated. Among subjects being studied are: flood-design studies using different heat factors involved in snow melting, and effects of physical characteristics on runoff; long- and short-wave solar radiation, albedo of snow, distribution of snow-pack water equivalent, snow cover as a function of terrain factors, area-mass-frequency of the snow pack, performance of hydrologic and meteorologic instruments, and development of indices to areal distribution of snow pack as it affects stream flow. Two special projects of the Corps of Engineers are currently active. Project CW-170 concerns the development of a radioactive isotope snow-measuring instrument and of means for automatically transmitting the measurements by radio. Project CW-171 is aimed at expediting the analysis of phases of the investigations of special interest to the Corps of Engineers and to provide for the training of personnel. Streamflow hydrographs, procedures of estimation of heat exchange by degree-day factors, estimation of permanent losses and computation of the discharge hydrograph by unit-graph, and similar procedures are being studied.

George W. Craddock (Intermountain Forest and Range Experiment Station, Ogden, Utah)--The highlights of two studies of the Station are as follows: (a) Snow observations, Snake River, Idaho and Wyoming - During the winter, spring, and early summer of 1950, the effect of forested and open areas on interception and melting of snow was studied on 17 pairs of plots and the effects of slope, elevation, and exposure on snow-melt rates was observed on 27 open snow courses. These plots and courses ranged in elevation from 4000 to 9600 ft and were located on the Boise, Payette, Targhee, and Teton National Forests. Owing to interception losses up to the start of the spring snow melt, closed sapling stands averaged 1.0 inch less water equivalent in the snow pack than adjacent open areas; closed pole stands averaged 4.0 inches less; open mature stands averaged 7.0 inches less; and closed mature stands averaged 14.0 inches less. Daily snow melting rates varied from 0.2 to 1.0 inch on forested areas, from 0.5 to 1.5 inches on large, level openings, and from 0.4 to 1.2 inches on small clearings. This study is being continued. (b) Snow accumulation and melting in ponderosa pine - An analysis was made of three years of snow measurements on some ponderosa pine lands near Idaho City, Idaho. In this study, snow was measured at 15-day intervals from January 1 to April 15 at 258 sampling stations. The water equivalent in the snow pack on north slopes averaged 5.32 inches as compared to 2.67 inches on east aspects, 2.29 inches on west aspects, and 0.68 inch on south aspects. Greatest depths of water occurred in sapling stands and in small brush openings on all but north slopes. On the latter, the greatest depth occurred in large brush openings. Smallest maximum depth occurred in large brush openings on south slopes. Some management implications: greatest snow storage and retention effects can be obtained by creating large openings in the forest stand on north slopes. Numerous small openings and a high percentage of sapling stand area would be almost as effective. Large openings should be avoided on the sunnier aspects. A report of this study is being submitted to the Journal of Forestry.

E. G. Dunford (Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.)--This station is actively engaged in several projects at the Fraser Experimental Forest in the Continental Divide Region of Colorado, designed to show the influence of lodgepole pine and Engelmann spruce - alpine fir timber types - on accumulation and melting of snow. (a) Effect of harvesting mature lodgepole pine - Twenty 8-acre plots have been harvested at varying degrees of timber removal to learn the effects on water available for stream flow from snow and rain. The first phase has been completed and reported in USDA Technical Bulletin 968. Study is continuing. (b) Effect of thinning young lodgepole pine - Forty-year-old lodgepole pine was thinned by two methods on 12 one-acre plots and the results compared with unthinned plots. Both methods of thinning - crop-tree and single-tree selection - allowed greater amounts of snow to be stored on the ground to be available for spring melt and runoff. Crop-tree thinning consisted of clearing around the most promising trees for a distance of eight feet radius. Single-tree thinning was done by selection on the basis of uniform spacing, allowing eight feet between trees and removing all intervening trees. The study is continuing. A published report will soon appear in the Journal of Forestry. (c) Effect of harvesting Engelmann spruce and alpine fir - Three methods of cutting have been tried consisting of tree removal in alternate cleared strips, in group openings, and by individual tree selection on eight-acre plots. In all cases 60 pct of the volume was taken out. No difference in snow accumulation could be detected between cutting methods, but in all three cases more snow was stored than in an adjacent uncut plot. The first phase of the study is still unfinished and no published results are available. (d) Application to watershed management - Coincident with the above tests, preparations are being made to test the overall effects of timber cutting on stream flow from a 710-acre watershed. Both lodgepole pine and spruce-fir types are found there. A one-foot San Dimas flume has been employed since 1939 to measure stream flow under undisturbed conditions. Snow accumulation and melt have been measured on an index course to associate these factors with measured runoff. Similar measurements are being made on an adjacent check watershed which will serve as a basin for estimating effects of timber removal on the test watershed. An access road is now being constructed for logging purposes. (Cooperative Snow Investigations at the Fraser Experimental Forest are described later in this report by J. R. Riter.)

Periodic frost observations are being made by the Northeastern Forest Experiment Station, Upper Darby, Pa., in New England, New York, and upper Pennsylvania to determine the effect of cover type and site condition on ground freezing in the northeastern United States. Analyses show the following factors to be significant in the formation of "concrete" or "impervious" frost:

(a) temperature deficiency accumulation, (b) average temperature on day of observation, (c) depth of snow mantle, (d) soil drainage, (e) land use, (f) litter depth, and (g) humus type.

In the autumn of 1949 a snow and frost study was initiated in the Pacific Northwest by the Division of Flood-Control Surveys of the Pacific Northwest Forest and Range Experiment Station, Portland, Ore., to determine the occurrence and character of frost under the dominant forest and range conditions of the region. The experimental area included the Cascade Range and the grazing lands in eastern Oregon and Washington. Forty-five plots were located on representative sites in forest and range types. Periodic observations were made monthly through the winter and bi-weekly during the spring snow-melt period. The periodic observations at each plot included: snow depth; snow-water equivalent; frost depth, type, and location in the soil profile; and soil moisture. The forest soils of the high Cascade forest, both east and west sides, remained unfrozen throughout the winter and spring of 1949-50. Discontinuous permeable frost occurred in the ponderosa pine and grass types at the lower fringes of the east-slope Cascade forests and impermeable concrete frost occurred in the sagebrush types and grass ranges of eastern Oregon and Washington during the winter and spring snow-melt period. To determine the effect of stand density on snow accumulation and frost occurrence, eight of the above plots were established in Douglas-fir stands which had undergone different cutting intensities. No frost occurred on any of these plots. Clear-cut differences in snow accumulation and recession under different crown densities were observed. In 1951 the frost study was confined to the sagebrush type and grass ranges of eastern Oregon where last year's study showed impermeable concrete frost occurring. Thirteen study plots have been established. These are being visited bi-weekly and observations will continue through the melt period.

George R. Free (Soil Conservation Service, Ithaca, N. Y.)--Investigations of the effects of snow, frozen soil, and soil moisture as related to runoff from experimental watersheds have been on a stand-by basis since 1947 due to lack of funds and personnel. Recently, operations have been resumed on a limited basis, but no new analyses have been completed to serve as a basis for a report at this time.

Albert S. Fry and W. C. Ackermann (Tennessee Valley Authority, Knoxville, Tenn.)--The Great Smoky Mountains snowfall investigations are a cooperative project between the U. S. Park Service, the U. S. Weather Bureau, and the Tennessee Valley Authority. The purpose of the investigation is to obtain essential information on snowfall and snow melt. The cooperative project has been carried on continuously since initiation in December, 1945. The area of investigation is along a profile across the Great Smoky Mountains which form the boundary between Tennessee and North Carolina. Stations are within the Great Smoky Mountains Park area and extend in a general southeasterly line from Gatlinburg, Tennessee, to the vicinity of Cherokee, North Carolina. Snowfall and its water equivalent, as well as snow on the ground and its water equivalent, are measured daily at eight locations. At six of these stations continuous records of temperature and relative humidity have also been maintained. Records are processed currently and are available in the offices of the cooperating agencies.

Kenneth J. Granbois (Safe Harbor Water Power Corporation, Conestoga, Pa.)--Tests have been authorized on the disintegration of river ice sheets by the use of black compounds on the ice surface and by the use of air bubbling from small holes in a submerged pipe line extending 1500 ft upstream and perpendicular to the dam. This idea worked fairly well during the 1950-51 season and kept an open channel in the pack and thus reduced resistance to flow when the pack was moved. A very sensitive resistance temperature recorder has been developed to record the river temperature to 0.001°C. When rapid cooling is recorded through zero C, frazil ice results, whereas cooling at a slower rate results only in the formation of sheet ice. Supercooling of the river has been recorded up to minus 0.015°C; as far as known, this is the first time this phenomenon has been observed outside the laboratory.

Milton Greenberg (Base Directorate for Geophysical Research, Air Force Cambridge Research Center, Cambridge, Mass.)--The Directorate has released Geophysical Research Paper No. 6, Air-coupled flexural waves in floating ice, by F. Press, M. Ewing, A. P. Crary, S. Katz, and J. Oliver, November, 1950.

L. L. Harrold and F. R. Dreibelbis (Soil Conservation Service, Coshocton, Ohio)--Current investigations at the Coshocton Hydrologic Research Project on snow and frozen soil include measurements of snow and depth of frost penetration on wheat and meadow watersheds. Soil temperatures at depths of 1/2-, 3-, 6-, 12-, and 24-inch depths are obtained together with air temperatures at 2 and 30 inches in the canopy on a rotation (No. 109) and on a woodland watershed (No. 131). Hydrologic measurements including precipitation, surface runoff, percolation, evapotranspiration, and condensation are also being obtained and are available for any possible correlation with either snow or frost depth penetration. Data indicate that frost penetration through its influence on percolation and resultant available storage may affect infiltration for a considerable time after the frost period. Work on characterizing different types of frost structure in the soil is being continued. The effects of three distinct types of frost structure (concrete, honeycomb, and stalactite) upon infiltration have since been confirmed by other workers. A fourth type of frost structure, the platy, has recently been identified and lies between the concrete and honeycomb in its density and porosity characteristics. The most recent development at this station deals with a rapid method of evaluating the water content of snow by obtaining electrical resistance measurements on Fiberglas soil-moisture blocks [Trans. Amer. Geophys. Union, v. 32, p. 447, 1951] set in the snow at various depths. Data on their use are insufficient at this time to warrant their recommendation. It appears, however, that they may have a good possibility, as reliable records have been obtained at this station in snow varying in water content from 15.9 to 40.8 pct. More observations are needed.

Oliver Kehrlein (Sierra Club of California, San Francisco, Calif.)--Reports on the activities of a group of members of the Sierra Club, Gene Serr, II, and Gene Serr, III, assisted by Jim Koontz, Fred Strauss, and Tom Henderson. They undertook to measure runoff from a small isolated snowbank at about 12,200 ft elevation in the Middle Bishop Creek country of California. The bank was sampled at the beginning and at the end of a two-week period during which runoff was measured. Data indicated that approximately 99 pct of the water equivalent of the snowbank actually ran off as water. In a 24-hour snow-block melting test at the same location about 97 pct of the water equivalent of the weighed block was recovered as runoff. These data are not in agreement with the prevalent idea that little runoff is yielded from elevations 12,000 ft above sea level in California.

Joseph Kittredge (School of Forestry, University of California, Berkeley, Calif.)--In the project on the evolution of the snow cover at elevations between 5000 and 6000 ft in the Stanislaus River drainage, some interesting indications have been obtained. The density of the snow under the crowns of the trees is from one to seven per cent greater than in the openings. The date of occurrence of maximum water equivalent of the snow may be as much as 50 days later than the date of maximum depth. The water equivalent of the snow in openings between the crowns is greater than under the crowns and may be greater than that in large clearings. Seasonal evaporation from snow was from 0.1 to 0.3 inch per month. Evaporation from snow decreased and was exceeded by condensation as spring advanced. Evaporation from water in the spring may be many times that from snow in the same pans. Evaporation in large openings between the trees is less than under the crowns, and in the small openings in dense stands it is greater. After the first bare ground appears, the mean decrease in percentage of area covered by snow varies with the cover from four to 17 pct per day.

Howard Lee (Arapaho National Forest, Idaho Springs, Colo.)--An avalanche-hazard forecasting study, patterned in general upon the work of Montgomery Atwater in Utah but with modifications to suit Colorado conditions, has been established in Colorado. It has been set up for a ten-year period. Air temperature, relative humidity, and wind are being recorded. Total snow depth, rate of snowfall, rate of settlement, and rate of wind deposit on critical areas are being observed. The time of occurrence and location of every slide in the general vicinity of Berthoud Pass, Colorado, the location of the intensive observations, are noted. The Colorado State Highway Department and the National Ski Patrol are actively participating in this project. Each slide is studied to learn what happened and why. Penetrometer surveys are conducted periodically to determine the structure of the underlying snow strata. Some of Andre Roch's formulas and theories are being applied. Resistance to shear is being measured with frames and balances devised to provide data for Roch's formulas.

Arno T. Lenz (University of Wisconsin, Madison, Wis.)--Reports upon investigations of snow melt - runoff relationships in the upper Wisconsin River Basin, using precipitation records and measurements of snow cover at two-week intervals throughout the winter. This study is being conducted by the University in collaboration with the Wisconsin Valley Improvement Co. of Wausau, Wisconsin. Soil-moisture measurements under the snow cover have been made for a number of years at selected points in the drainage basin.

K. A. Linell and Elliot F. Childs (Corps of Engineers, New England Division, Boston, Mass.)--The Frost Effects Laboratory of the Corps of Engineers, Boston, Mass., is performing extensive tests to study the susceptibility of soils to frost action and to investigate description, classification, and strength properties of frozen soils. Ultimate objective is to arrive at improved engineering design methods, data, and criteria for situations where frost damage is a possibility or where frozen soils are encountered in foundations. Studies of frost susceptibility are being performed for the Airfields Branch, Office of the Chief of Engineers, and studies of the description, classification, and strength properties of frozen soils are being performed for the Snow, Ice, and Permafrost Research Establishment. The tests are being performed in the laboratory cold rooms on specimens frozen slowly from top to bottom at rates of 1/4 to 1/2 inch per day penetration of freezing temperature. Crystal structure in ice lenses formed in the frost susceptible soils is being studied and compared with structure in control specimens of plain ice frozen by the same procedure.

Duart A. MacLean (Water Rights Branch, Dept. of Lands and Forests, British Columbia)--The investigations on snow made in Canada could properly be divided into two main classifications: (1) hydrologic investigations and (2) physical investigations. Hydrologic investigations - Snow surveys have been and are being made in Canada for the purpose of forecasting subsequent runoff in British Columbia, Alberta, and Ontario. The snow surveys in British Columbia, under the direction of the Water Rights Branch, have been in operation for about 17 years and at present about 65 snow courses are sampled, mostly in the Columbia River Basin. Runoff forecasts are based on past records of snow-water content, runoff, and precipitation. No attempt is made to forecast peak flows. A network of snow courses covering the Fraser River Basin is being established. Snow surveys are conducted in Alberta on the eastern slopes of the Rocky Mountains by the Water Resources Division of the Dominion Department of Resources and Development. The Ontario Hydroelectric Power Commission also carries out snow surveys for the purpose of forecasting stream flow. The Dominion Department of Agriculture has a range Experiment Station near Kamloops, B. C., which obtains and uses snow-water data for the purpose of correlating with stream flow, soil moisture, and plant growth. This phase of their work is at present in an early stage. Meteorological stations across Canada, operated by the Meteorological Services of the Department of Transport, measure the depth of snow after each snowfall and reduce this to water by assuming the density of newly fallen snow is ten per cent.

Physical investigations - The Soil and Snow Mechanics Section of the National Research Council of Canada, realizing the great influence snow plays on the economy of Canada in peace and war, has led the Canadian research on snow. During the recent war they assisted in the development of more efficient over-snow vehicles, both track and ski. Since the war this research has expanded to snow clearance, snow fences, and avalanche studies. Translations have been made of important foreign research, particularly from Switzerland. In 1946 a broad study was inaugurated and a Canada-wide snow survey was established to find the limiting characteristics of snow types in Canada. This work has been, and is being, conducted with the cooperation of the Meteorological Service of the Canadian Department of Transport. Tests made are as follows: (a) air temperature (one to three feet above snow surface), (b) snow temperature (at least every six inches through depth), (c) specific gravity (observations in each distinct layer), (d) free water content (calorimetric method), (e) grain size and shape (by inspection and measurement), (f) snow hardness (measurement of resistance to penetration), and (g) form of snow surface (by inspection). The locations where daily measurements are taken have been open and unsheltered. This important work is being carried on, and in the future sheltered locations will also be used. Certain research has been carried out by the Canadian Department of Transport on maintenance of airport runways during winter. Rolling of snow instead of clearing it has developed from this research. The Meteorological Service and the National Research Council have carried out certain studies in the artificial production of snow. The Arctic Institute of North America has carried out a number of projects, the results of which have made available many data, particularly with regard to firn densities. The latest project was an expedition to an ice cap on Baffin Island in 1950. Some of the universities in Canada, alive to the necessity of snow research, are carrying out limited research. The National Research Council of Canada publishes information and bibliographies of this and other research in The Canadian Geophysical Bulletin which is issued quarterly by the Associate Committee on Geodesy and Geophysics, the National Committee for Canada of the International Union of Geodesy and Geophysics.

Choji Magono (Hokkaido University, Sapporo, Japan)--In those fields of investigation where the integrated value of temperature is of more significance than the instantaneous value it is desirable to have an instrument which can show the integrated value of temperature directly. By the use of the variation of viscosity of liquids with temperature, a series of integrating thermometers were built which can be used easily in the laboratory and even in the field. [See Design of an integrating thermometer, J. Faculty Sci., Hokkaido University, Japan, Ser. 2 (Physics), v. 4, no. 1, pp. 1-19, February, 1951, by the writer.]

J. S. Marshall (McGill University, Montreal, Canada)--For the past five years Stormy Weather Research Group at McGill University has been studying the physics of clouds and precipitation by radar and by related laboratory experiments. Currently snowflake size distributions are being investigated along with radar observations of the snow. The development of methods of extracting samples of snow from a storm in order to determine size distributions and snow densities, is a part of this experimental program. Preliminary investigations are under way in the laboratory to determine the heat transfer from falling snowflakes and to study the melting of flakes and aggregates. The work of the group is supported in part by a grant from the Defence Research Board and a contract for theoretical work with the Geophysical Directorate of the United States Air Force. Topics under study include: frequency analysis of a radar pulse returned from a random array of scatterers; an assessment of the applicability of various formulas for particle-size distributions; the effect of particle shape on radar echoes from ice cloud and snow, and a review of all cloud and precipitation studies by radar.

O. W. Monson (Montana State College, Bozeman, Mont.)--Since August, 1948, A. R. Codd of the Soil Conservation Service has been in full charge of snow measurements throughout Montana and Wyoming. Methods of conducting the surveys have improved or, at least, they have changed a great deal, the most remarkable change being that of reaching the snow courses by airplane instead of the slower and more laborious snowshoe method. Codd recently reported a series of snow measurements made by plane for the sum of $27. The same measurements made by the old methods would have cost nearly $200. We are still working on a machine for over-snow transportation which shows considerable promise. It is a low-cost pontoon-type vehicle which will carry two men and travel over all kinds of snow. More will be heard about it at a later date.

Ukichiro Nakaya (Hokkaido University, Sapporo, Japan)--(1) Electron microscopic study of snow-crystal nuclei - This study was carried out chiefly by Motoi Kumai, Assistant of Hokkaido University. The experiments were carried out at Mt. Taisetsu, the altitude being 1050 m. The snow crystal is received on a collodion film of the holder of electron microscope, and is left in a desiccator which is kept at the temperature between -4°C and -8°C. The crystal evaporates by sublimation and the supposed nucleus is left on the collodion film. This specimen is brought under an electron microscope. One solid nucleus is always observed at the central portion of snow crystal, which is proposed to be called center nucleus. The center nuclei are 0.5 to 8μ in the largest extension. At the other part of snow crystal numerous smaller nuclei are observed, which are nearly the same in size as the condensation nuclei in the free atmosphere, that is, 0.01 to 0.1μ in diameter. Forty-three successful photographs of center nuclei were obtained, most of them estimated to be soil particles, some being lumps of carbon particles, micro-organism, or hygroscopic particle of some chemical compounds. Sixty photographs of condensation nuclei were taken, and the frequency curve of the size is made with 1200 data. Condensation nuclei are found to be composed of two kinds, the most frequent value of the larger ones being about 0.15μ in diameter and the smaller 0.05μ. The mechanism of snow-crystal growth is discussed from these data, and the aerosol theory of snow-crystal formation is proposed.

(2) Snow survey in Japan - This research was carried out chiefly by Juji Sugaya, Assistant of Hokkaido University. The elaboration and extension of his former study of snow survey in the basin of Mt. Taisetsu was done in the succeeding two winters. Practical method of determining the absolute amount of snow deposited in a vast region was devised. The principle is to find the number of spots, the data at these spots representing the mean value of the total snow deposit in that basin. The mode of winter precipitation in mountain districts was studied by a "stratographic method." Several powders of different colors were scattered over the snow surface at suitable intervals; for example, every two or three weeks. At the beginning of spring, when the snow deposit reached the maximum depth, a large hole is dug in the snow cover. By examining the colored lines, the mode of snow precipitation during the winter is made clear. The runoff due to the melting of snow is studied in connection with the amount of snow melted by that time. The latter was estimated from aerophotographs taken at three stages of snow melting. The Japanese Government proposes to carry out a similar snow survey in the basin of Tadami River, where we can expect three million KW of water resources. The survey was started in November, 1950.

J. R. Riter (Chief, Hydrology Branch, Bureau of Reclamation, Denver, Colo.)--(1) Hydrologic investigations - The Hydrology Branch has been collaborating since 1946 with the Rocky Mountain Forest and Range Experiment Station, Forest Service, in a cooperative snow investigation at the Fraser Experimental Forest about 75 miles west of Denver, Colo. Broad objectives are to improve the accuracy of seasonal water yield and forecasts of runoff rate, and to secure more precise information on rates of runoff from snow melt. Five sub-projects have been reported upon: (a) the performance of shielded precipitation storage gages; (b) methods of interpreting the commonly available daily maximum and minimum temperatures in terms of degree-days; (c) analysis of rates of snow melt; (d) calculation of evaporation losses from snow; and (e) synthesis of rate of runoff from snow-melt hydrographs. Report No. 1, The 1948 snow-melt season - Progress in snow-melt investigations at the Fraser Experimental Forest, November, 1949, was released by the Bureau of Reclamation and the Forest Service. Five sub-projects are reported in Report No. 2, The 1949 snow-melt season, June, 1951. The gathering of intensive field data was terminated with the 1950 snow-melt season, and efforts are now being concentrated upon analysis of the data. The Bureau of Reclamation is collaborating with the Weather Bureau upon a snow-melt investigation in the Heart River Basin of North Dakota. Cooperative observers have been supplied with snow-sampling equipment especially designed for use with shallow-depth and possibly high-density snow. This network has been established to provide data on the release of runoff from snow melting in the Great Plains.

(2) Ice pressure investigations by the Engineering Laboratories Branch, Bureau of Reclamation - In the design of some dams and accessory structures it is necessary to consider the effects of the thermal expansion of thick ice sheets. Only a very few attempts have been made in the past to determine the magnitude of ice thrusts by actual field measurements. A major part of this program has been necessarily concerned with the design and perfection of suitable pressure gages. Two types of gages have been developed and used successfully for field measurements at Eleven Mile Canyon Reservoir in Colorado. The gages are described and the results are given in Laboratory Reports SP-16, SP-21, SP-22, and SP-28. A part of the program has been directed to securing a better understanding of the factors influencing ice pressures. One of these factors, the relationship between rate of ice temperature increase and the pressure developed in a restrained ice specimen, has been under investigation in the laboratory for the past several months. This work has not yet been described in a formal report. A summary of the ice pressure investigations forms part of "A symposium on ice pressure" to be published by the American Society of Civil Engineers.

Vincent J. Schaefer (General Electric Research Laboratory, Schenectady, N. Y.)--A number of basic research studies related to the formation of snow, frost, and ice crystals have been made in this laboratory by Bernard Vonnegut and Vincent J. Schaefer. Vonnegut's activities have been concerned recently with the development of instruments for continuously measuring the concentration of condensation and ice nuclei in the free atmosphere. Schaefer has devoted considerable research effort to basic studies of such things as the formation of frazil ice in running streams, as well as under the microscope, and has recently completed a study of the rate of growth of snow crystals in supercooled clouds. A new method for studying the structure of glacier ice was devised by him during a short visit to the Snow and Avalanche Research Institute on the Weissflujoch near Davos, Switzerland. More than 8500 observations of the concentration of ice crystal nuclei in the free atmosphere have now been made under his direction at the Mt. Washington Observatory. These data established for the first time a 39-month study of this important feature of the atmosphere. The results show that the concentration of such nuclei varies by a factor of more than a million-fold and that the variations seem to be related to the trajectory of the air reaching Mt. Washington. The study shows that the high concentrations occur in air which has passed over the semi-arid regions of the West. It also shows that the concentration is very low about half of the time. This fact probably accounts for the uncertainty of predicting icing clouds and certain types of storms which develop from large vertical thicknesses of supercooled clouds. A number of snow studies have been made at the Mt. Washington Observatory in addition to the ice nuclei studies. Among such projects was one directed toward a method for determining the amount of blowing snow in a particular snowstorm. This utilized a snow catcher mounted on gimbals and vaned to catch only that snow carried by the wind.

Lewis H. Stolzy (Soil Conservation Service, East Lansing, Mich.)--Weekly snow surveys are being performed on three small watersheds. In cooperation with the Weather Bureau, a snow-survey system has been established in the Saginaw River Valley, the results of which are made immediately available to the Weather Bureau for use in flood forecasting.

R. F. Taylor (Alaska Forest Research Center, Forest Service, Juneau, Alaska)--The Center is not carrying on any snow research.

C. C. Warnick (Engineering Experiment Station, University of Idaho, Moscow, Idaho)--At present the Engineering Experiment Station has in progress a research project on a study of high-altitude precipitation gages. It is particularly concerned with a study of windshields and their behavior during snowstorms. During the past years, tests have been conducted in a new wind tunnel on the relative catch performance of various types of gages with and without windshields. Sawdust was used to simulate blowing snow. An attempt has been made to determine the theoretically true catch by using special photographic techniques. A new field station with two gages was established at Priest River Experimental Forest and the seven gages at Mullan Pass are still in operation with various types of windshields installed. This work is under my direction and has had, as a part-time participant, M. Gurevitch of the Physics Department. Austin E. Helmers of the Forest Service is cooperating in the observing of the test gages at Priest River Experimental Forest and S. W. Harrison of the CAA cooperates in observing at the field station near Mullan Pass, Idaho.

Walter T. Wilson (Weather Bureau, San Francisco, Calif.)--In the Weather Bureau program for continuing improvement of methods for forecasting stream flow, there are no pertinent developments to report in water-supply forecasting, the procedures for which are fairly well stabilized and are in the literature. In improving the forecasting of stream flow from melting snow, and from rain on snow, a recent appraisal has indicated that the greatest opportunity for improvement is in developing better methods for observing, reporting, and applying data on areal distribution of active snow cover. A Snow Cover Investigations Unit has been established for this purpose in the River Forecast Center at Portland,Oregon. Participation continues in the Cooperative Snow Investigations of the Weather Bureau and the Corps of Engineers.

R. A. Work (Supervisor of Snow Surveys, Soil Conservation Service, Medford, Ore.)--The activities of Soil Conservation Service, Division of Irrigation and Water Conservation, in collaboration with various educational institutions or State Experiment Stations, during 1950-51 are as follows: The program of snow surveys was expanded, notably in Montana in collaboration with Montana Experiment Station, U. S. Bureau of Reclamation, and the U. S. Forest Service, and also in Colorado. Leaders of this particular expansion activity have been A. R. Codd, Homer Stockwell, and Jack Washichek. During 1950-51, in all of the western states, nearly 900 men measure more than 1000 snow courses. In collaboration with Utah Experiment Station, research is being continued to delineate factors other than snow which affect the snow cover - runoff relationship. The leader of this project is Gregg Pearson, SCS and USAC. Arrangements have been made for the establishment, for the Bureau of Reclamation, of snow courses in Eklutna and Swan Lake drainage basins in Alaska. Studies were continued on research and development of over-snow mechanized vehicles, notably in collaboration with Utah Research Foundation, but also with collaboration from Oregon Agricultural Experiment Station and continued cooperation with Montana State College. These investigations included observations of performance of all known over-snow machines. The principal workers in this field are Ross Eskelson, Gregg Pearson, A. R. Codd, R. A. Work, and O. W. Monson. The use of over-snow vehicles in snow surveys has grown to such proportions that effects of such vehicles upon distortion of snow-water equivalent, if machines be driven upon snow course, merits attention. A simple project to analyze importance of this unknown is headed by Gregg Pearson of SCS, collaborators being M. W. Nelson, A. R. Codd, Robert Beaumont, Homer Stockwell, and Jack Washichek, all of SCS and various state colleges. Work was conducted on evaluation of results of cloud nucleation experiments in Oregon on a large scale in collaboration with Oregon State Experiment Station, with several irrigation districts, and with some private corporations. Methods of evaluation have been developed which utilize precipitation samples. This work is conducted by Robert T. Beaumont and W. T. Frost of OSC and SCS, respectively. Studies of the effect of ground-water departures from normal upon runoff of streams as a feature of water-supply forecasting by snow surveys are being continued in Nevada by Clyde Houston of SCS and Nevada Experiment Station.

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Transactions, American Geophysical Union Volume 34, Number 1 February 1953

REPORT OF THE RESEARCH COMMITTEE ON PRECIPITATION, 1951-1952

W. C. Ackermann, Chairman

M. L. Albertson
G. L. Barger
Henry Demboski
William E. Hiatt
Loyal A. Johnson
Joseph Kittredge
Arno T. Lenz
Franklin F. Snyder
C. C. Warnick

The members have cooperated splendidly in advancing the objectives of the Committee which are to suggest, stimulate, coordinate, and report on research in precipitation. They have reported several research investigations, reports on some of which will be presented in subsequent issues of the Transactions and at future annual meetings. Kittredge of the University of California reports a study on the influence of forests on snow. This deals with the density of freshly fallen snow in the open and under the crowns of trees. A relation has also been established between the water equivalent of snow intercepted by the crowns and the amount of precipitation per storm.

In another study on the West Coast, attention is being given the size of raindrops and the intensity of rainfall measured beneath trees, including both rain and the drip from fog which is an important factor on the Pacific slopes.

At the Priest River Experimental Forest in Idaho the U. S. Forest Service is carrying on an intensive program of observations and evaluations of precipitation on a small mountain watershed.

By way of reporting current developments in the field of precipitation, the plight of the Hydroclimatic Network of the U. S. Weather Bureau is of concern to all hydrologists. This Hydroclimatic Network, which includes about 2300 recording and 600 non-recording rain gages, was placed on a restricted basis during the past year, and processing and publication of hourly precipitation data were stopped as a temporary expedient. The Hydroclimatic Network is a special network established in 1937 and not to be confused with the regular climatological network of daily precipitation and temperature stations of the Weather Bureau. The Hydroclimatic program is financed primarily by transfer of funds from the Corps of Engineers, and the amount of money available during 1952 was reduced as a result of appropriation action of the Congress. Future prospects for the Network are somewhat in doubt for the time being. If funds continue to be restricted, the question of non-processing of data versus closure of an appreciable number of the stations will have to be decided.

As to future activities in the field of precipitation, the Committee looks for continued study of virtually each operation and each technique leading to further refinements.

One activity which we believe should be intensified is the role of the hydrologist in the evaluation of artificial nucleation. This has been proven to be physically possible, but there is a vast amount of research, study, and thought which must go into it before it can be depended upon and predicted with any degree of accuracy. The problem is somewhat like atomic energy – for some time it was known that atomic energy was theoretically possible but a tremendous amount of effort went into the development of it from the practical viewpoint. Furthermore, weather control has possibilities, when all of the ramifications are considered, that may make it rival atomic energy in importance.

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DISCUSSION OF

"PRECISION LEVELING AT THE WHITE HOUSE"
by HOWARD S. RAPPLEYE

[Trans., v. 33, pp. 1-7, 1952]

F. Lionel Peckover (Division of Building Research, National Research Council, Ottawa, Canada)--The author has given an interesting and enlightening account of the difficulties met in keeping accurate levels on a site which is being used for construction operations. He and his assistants are to be congratulated on the patience and ingenuity they showed in carrying their job to a successful conclusion.

From the nature of the work described in the paper, it is evident that the expense involved was by no means negligible. The author was fortunate that in this case the size and public importance of the White House project ensured that the necessary funds were provided, once the need for keeping accurate level records was recognized. On less important construction jobs, the cost of such a task is often a stumbling block, even when the resulting records might be considered an essential part of good construction practice. Certainly the obstacles reported in the paper are not encouraging to anyone planning similar work with limited funds at his disposal.

It is felt that this discouraging picture calls for some comment. This discussion is intended to suggest an alternative method of precise leveling to that described in the paper, which would yield sufficiently accurate results at considerably less expense.

The problems which Rappleye has encountered are, of course, not new. Engineers have struggled with them for centuries, usually with the aid of precise optical measurements. In 1933, however, a significant improvement on such methods was suggested by TERZAGHI [1933, 1938], whose work has inspired much of the present knowledge of soil mechanics. He proposed the use of liquid as a leveling medium and showed that measurements could be taken by this means both easily and accurately.

In this method, the surveyor's precise level is replaced by a long flexible hose filled with water. To each end of the hose is attached a short vertical glass tube in which the water level is read. The two ends of the hose are hung on two observation stations, installed at an approximately constant elevation in walls or columns, for which the difference in elevation is required. A comparison of the water levels at each station will then give this difference with accuracy. Observation stations are usually distributed inside a building so that surveys may be closed and the closure error distributed.

The water level in the glass tubes may be read most accurately with a point gage. It has been the writer's experience, however, that readings accurate enough for all ordinary purposes may be made more easily with a metal sleeve sliding over the glass tube and raised to the bottom of the meniscus. The reading is then made on a vertical scale and vernier. Further details of the writer's design of apparatus are shown in Figure 9; its operation has been described [PECKOVER, 1952].

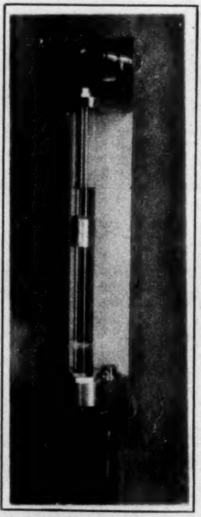

Fig. 9--Water-tube level in operating position

In conducting level surveys in buildings, observation stations are naturally of prime importance. When construction work is going on, suitable stations are particularly difficult to establish, as

Rappleye has pointed out. Construction workers have a well-deserved reputation for being able to damage any special installation near which they work, unless it is protected or hidden with a high degree of cunning.

In his original work, Terzaghi devised a form of wall plug to be used in surveys where damage was likely to occur, and the writer has also used this with complete satisfaction. At the point where an observation is to be made, a metal socket is cemented tightly into a drilled hole so as to be flush with the surface of the wall or column. This socket is ordinarily provided with a flat threaded cover with an identifying number. When a reading is to be taken, the cover is replaced by a threaded plug which protrudes from the wall far enough for the water tube level to be clamped to it (see Fig. 9).

A disadvantage of the water-tube level is that it will not measure a difference in level of adjacent points of more than about nine inches, and observation stations must be located with this in mind. In actual practice, this is very seldom found to be a handicap.

In surveys with this level, practically all of the significant errors can be eliminated by reversing the two ends of the instrument on each pair of observation stations. Differences in temperature over the route of the survey sometimes introduce difficulties, since they change the density of the water in the vertical parts of the hose, but these are overcome by insulating the affected parts and taking readings as rapidly as possible in critical locations.

The accuracy of this apparatus is sufficient to locate the level of each point in a closed survey to 0.08 mm. This accuracy is exceeded by leveling methods such as those used by Rappleye. It is, however, within the specifications to which he was working and it may be increased, if necessary, in the method of reading the water level, as mentioned before.

When the convenience of this method is also considered, it is suggested that it might well replace the more conventional leveling means in many special instances. In construction work its advantages are obvious. A line of sight is not necessary and so intervening walls, scaffolding, and the general paraphernalia of the job are no real hindrance. Similarly, bad weather conditions are not so great a deterrent. Distances between observation stations are limited only by the length of hose which may be as much as 100 ft. The procedure for use of the method is simple enough to allow two men to complete a building survey of 30 stations, with accompanying calculations, in a single day.

A most important part of level surveys is that all elevations must be related to one or more reference bench marks. These are presumably points which will move a negligible amount over the required period of time.

Bench marks may be placed either inside or outside the building concerned as long as they are carried to stationary strata. In either case they may be tied in to the survey with the water-tube level or a surveyor's level, whichever is more convenient.

Since it is a well-known fact that many types of soil are subject to small changes in volume with the wetting and drying effect of the various seasons of the year, the most reliable bench marks are usually chosen to extend below this influence, or to bedrock. It is therefore interesting to see the most satisfactory results which Rappleye has obtained with relatively shallow bench marks, and in this connection it would be interesting to know what type of soil generally prevails in the area. Those movements of his reference points which did take place do not seem to relate to any natural movements of the ground.

Lest it be thought that tree roots, hydrants, and foundations of small structures are always satisfactory reference points, an instance should be mentioned where two bench marks were chosen for a level survey on a new building in Ottawa. A hydrant (connected to pipes laid eight feet deep in this case) and a large house with a deep basement were used. The differential movement of the two bench marks has so far amounted to nearly one-half inch, and it is ironical to find that the movement of the two marks relative to each other has been considerably greater than the movement of the new building relative to either. The choice of reference points for the White House project seems to have been singularly fortunate.

This discussion is presented in the interests of improved surveying practice. All too often, accurate check measurements such as those described in the paper are omitted, or done so poorly as to be of no value, because their importance is not realized or they are thought to be costly and difficult to achieve. By the results he has presented, Rappleye has helped to show the type of detailed information which a survey such as this can yield. It is hoped that this discussion in turn has suggested a relatively economical method by which this information can be obtained.

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PECKOVER, F. L., A new water-tube level for measuring the settlement of buildings, Tech. Rep. 11, Div. of Bldg. Res., Nat. Res. Coun., Ottawa, Canada, Feb. 1952.

Howard S. Rappleye (U. S. Coast and Geodetic Survey, Washington 25, D. C., Author's closure)--The discussion of this paper by Peckover is constructive and without doubt adds materially to the published information on the subject of surveys for the determination of movement of structures. The writer feels that perhaps he was in a position from which he could not see the forest because of the trees. Therefore, upon receipt of a copy of Peckover's discussion, the writer referred it to Charles W. Barber, Chief Structural Engineer, Public Buildings Service, Washington, D. C., for comment. His reply is quoted in full, with his permission.

"I have read your paper 'Precision leveling at the White House' in the Transactions of the American Geophysical Union and the advance copy of F. L. Peckover's discussion.

"We were much concerned with the settlement of the White House walls, constructed 150 years ago of clay brick, lime mortar, and sandstone. Substantial evidence of settlement was visible. An accurate record of the wall elevations prior to and after reconstruction, as well as the vertical movement during the underpinning, were considered essential. The relatively slight additional cost of precise levels over the cost of levels of highly questionable accuracy is considered a good investment.

"Our previous experience with measurements of pile settlements in tests for the foundation of the General Accounting Office led us to precise levels and was our first experience with them on construction. Simultaneously we tried to use the water levels proposed in Peckover's discussion of your paper.

"We had previously had three of these levels made. They were essentially the same as the one in the photograph accompanying the discussion and as described therein.

"Our experience was most disappointing. The readings were quite unreliable. Water bubbles, temperature difference, and other unknown factors cast doubt on the readings so that we abandoned their use in favor of the precise levels which we will use on similar work where we require their reliability.

"An indirect benefit of your work on the White House is the accurate measurement of settlement as applied to the relatively new science of soil mechanics. These levels, and the subsequent ones which I trust will be made on the White House, will add considerably to the progress of our knowledge of building settlement and the resulting cracks."

One of the illustrations in the paper, Precision Leveling for Pile-Loading Tests [J., Coast and Geodetic Survey, no. 3, pp. 98-100, April, 1950] shows one of the water-leveling instruments attached to one of the steel "H" piles involved in the tests at the General Accounting Office.

Barber also furnished a blue-print copy of a drawing showing the complete logs of six test borings made near the White House. This information is too voluminous to reproduce here but is undoubtedly available to a serious student of this subject.

In brief, the ground elevations at the six test borings ranged from +54.8 to +55.5 ft. The test borings ranged in depth from 73.0 to 87.7 ft, with from three to ten feet of the bottom of each hole in "mica gneiss."

At the approximate level of the bottom of the new foundations, these logs show "coarse brown sand and gravel" quite uniformly.

Additional leveling has been done at the White House beyond that discussed in the original paper but no marked departure from normal behavior had developed up to the time the White House was reoccupied in the Spring of 1952. Gradual settlement was measured as the dead load increased while the reconstruction progressed to completion. As yet no levels have been run since the building was reoccupied.

DISCUSSION OF

"SOME EVALUATIONS OF SUSTAINED CLOUD-SEEDING OPERATIONS"
by I. P. KRICK and T. B. SMITH

[Trans., v. 33, pp. 53-56, 1952]

John Summersett (U. S. Corps of Engineers, Walla Walla, Washington)--The suggestion of an effect on monthly rainfall totals as a result of cloud seeding is based on deviation to the right of the regression line. However, as Krick and Smith point out, the deviation may even be great under natural conditions. In all but two of the seven evaluations, greater deviations than for the month of seeding has occurred in past years. Obviously, more years of seeding must be added to the record before an effect can be claimed.

If the seeding has been successfully restricted to the target area in Oregon and is effective, an area immediately to the north and one to the south must have experienced relatively less rainfall. This follows from the fact that the moisture-laden air flows strongly from the west. Accordingly, Figures 8, 9, and 10 were constructed to show this relationship. The control stations were related by simple arithmetic average (the alternative method mentioned by Krick and Smith) to similar averages for the three areas to the east.

Three stations were selected for the control area, Portland, Salem, and Eugene; they have nearly equal total rainfall amounts and adequately sample the airstream flowing to the eastern areas.

Six stations in the target area have 16 years of record from 1936 to 1951, inclusive. Records for the same period were found for six stations in an area of similar size immediately north, and one just south, of the target area. These stations are listed in Table 3.

Table 3--Target and vicinal stations, Oregon and Washington

Target, Ore.	Northern vicinal, Wash.	Southern vicinal, Ore.
Arlington	Bickleton	Antelope
Condon	Prosser	Grizzly
Heppner	Sunnyside	Madras
Kent	Wapato	Mitchell
Morgan	White Swan	Ochoco Ranger Station
Wasco	Yakima	Prineville

Analysis of Figures 8, 9, and 10 shows that 1950 data, despite seeding, fell almost on the line drawn through the aveaage of all years for the month of October for all three areas. In November, despite seeding, the rainfall in all three areas was less than expected from the amounts at the control stations, the deviation becoming uniformly greater progressing from north to south. In December, although 1950 data fell to the right of average in the target area as shown by Krick and Smith, it also fell to the right for the vicinal stations to the north and south. The fact that it fell a little farther to the right than for the vicinal stations is not significant, because the same condition existed for the years in which the monthly total rainfall at the control stations in November was 6.0, 3.2, and 5.0 inches, and in October was 4.2 inches.

Since Krick and Smith point out that the reason for not including 1951 data in the study was lack of complete precipitation data, it may be inferred that similar cloud-seeding experiments were performed during that year. Study of Figures 1, 2, and 3 shows that 1951 data fell to the left of average for October, and on the line for November and December; there is absolutely no indication of an effect due to seeding.

No attempt was made to make similar studies for the New Mexico and Colorado areas, because they do not have the steady airstream. In Oregon and Washington, at least, it can only be concluded that cloud seeding is ineffective.

T. B. Smith (American Institute of Aerological Research, Pasadena, Calif., Author's closure) --Summersett has pointed out an evaluation problem which has become apparent to us upon examination of additional Tri-County seeding data. It has now become clear that the sensitivity of the statistical tests mentioned in the original article for detecting possible seeding effects varies markedly from one area to another. This can be seen by the following analysis.

Several charts relating actual target and computed target area rainfall are shown in the original article. Each chart shows a scattering of points about the regression line which represents past unseeded years. An indication of seeding success is obtained if the point representing the seeded month falls to the right of the regression line (target rainfall greater than best estimate obtained from control area rainfall). Seeding could not be considered successful, however, unless points representing a number of seeded months consistently fell to the right of the regression line.

It is useful, therefore, to compute the increase in actual rainfall for each of the past years represented on the chart, which would be sufficient to cause the specified point to fall on or to the right of the regression line. This can be done for any particular past year by merely noting, from the chart, the actual rainfall corresponding to the plotted point and the actual rainfall corresponding to the regression line estimate. Since it is generally accepted that cloud seeding, as practiced at present, can only operate to increase natural precipitation, a conversion of these data into required percentage increases is desirable.

The results of the analysis are given in Table 4, based on 38 years of November data in Oregon and 46 years of July and August data (combined sample) for New Mexico. The interpretation of the following figures can be seen from these examples. If the rainfall for each of the past 37 Novembers in eastern Oregon was increased by nine percent, half of the 37 points would be located on the right side of the regression line. If each month's rainfall was increased by 108 percent, 0.9 of the 37 points would then be on the right side of the regression line. Applying the latter result to tests of seeding effectiveness, an increase of over 100 percent in November rainfall would be required to assure that the seeded month would fall to the right of the regression line with a 90 percent chance of occurrence.

Table 4--Percentage increase necessary to cause datum to fall to right of regression line

Location	Probability of occurrence (Number chances of 10)				
	5	6	7	8	9
Eastern Oregon	9	26	37	52	108
Northeastern New Mexico	0	10	15	33	42

The same type of analysis has also been carried out to indicate the percentage increases required to cause the seeded month to fall at the extreme deviation (to the right) which has occurred in past years (see Table 5).

Table 5--Percentage increase necessary to cause datum to fall at extreme deviation of past years

Location	Probability of occurrence (Number chances of 10)				
	5	6	7	8	9
Eastern Oregon	100	125	140	167	300
Northeastern New Mexico	43	51	64	85	100

The variability shown in these tables between eastern Oregon and northeastern New Mexico is due in part to the inherent variability between target and control areas. Another factor of importance, however, is the relative abundance of low rainfall years characteristic of eastern Oregon. Percentage deviations from the regression line and from the extreme of past years are usually substantially greater for those low rainfall years than those characteristic of wetter regions.

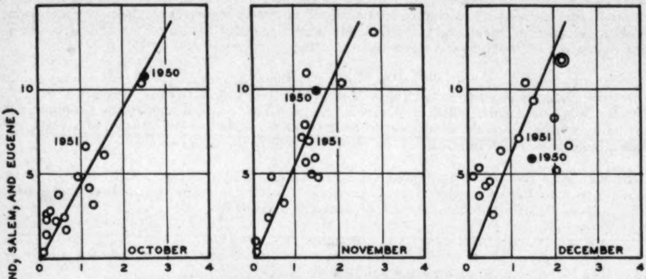

Fig. 8--Monthly total rainfall relation between control stations and northern vicinal stations, in inches

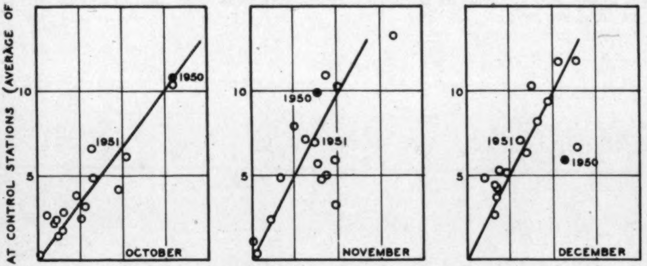

Fig. 9--Monthly total rainfall relation between control stations and target stations, in inches

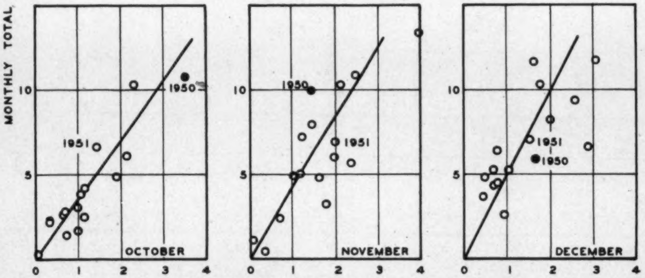

Fig. 10--Monthly total rainfall relation between control stations and southern vicinal stations, in inches

The difficulties involved in using the suggested statistical tests in eastern Oregon are clearly indicated by the necessity of increasing the precipitation by more than 100 percent in order to assure merely a 0.9 chance of the month falling to the right of the regression line. Even this sizeable increase and its indicated statistical result would not be acceptable as a major indication of seeding effectiveness.

It appears that the statistical test suggested in the original article is much more sensitive in detecting changes in northeastern New Mexico than in eastern Oregon. Consequently, the charts for July and August, 1950, in northeastern New Mexico, and August and September, 1950, in adjoining southeastern Colorado should be considered as better indications of seeding effectiveness than those covering October-December, 1950, in eastern Oregon.

To overcome the problems arising from the use of this particular test in eastern Oregon, we have turned to analyses of individual storms and a comparison with previous unseeded storms. Thus the need for outside control areas is lessened.

It need hardly be pointed out that the foregoing remarks on variability between target and control areas apply also the the use of Summersett's vicinal areas. In addition, his northern vicinal area includes another adjacent seeding project.

Summersett's closing remarks on the uneffectiveness of cloud seeding in eastern Oregon should be modified to read that cloud seeding in this area is not effective in producing the percentage increases (of the order of 100 pct) which are necessary to demonstrate effectiveness by the suggested method.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

BLATT, JOHN M. and VICTOR F. WEISSKOPF, Theoretical nuclear physics, John Wiley and Sons, 864 + xiv pp., $12.50, 1952

In their preface the authors say, "Nuclear physics is by no means a finished edifice. It is very much to be hoped that the fundamental laws can be discovered which will account for all the known properties of nuclei and will allow us to predict new, unknown properties successfully. At present we must restrict ourselves to the investigation and correlation of all known nuclear properties on a semi-empirical basis. This book is devoted in its entirety to this task."

This task is indeed an enormous one, which hardly any other authors have ever attempted to achieve in a textbook, mainly because of the rapidly accumulating experimental facts that demand interpretation. Although Blatt and Weisskopf state that they had to omit many details and special developments, this relatively small volume covers almost all the aspects of theoretical nuclear physics and critically distinguishes between well-established fundamentals and more speculative aspects.

The first of the 14 chapters of the book deals with the general properties of the nuclei and serves as an excellent introduction. In the next four chapters the problems of the lightest nuclei are treated, that is, the two-, three-, and four-body problems. Chapters 6 and 7 are devoted to "nuclear spectroscopy" and energetics. Chapters 8, 9, and 10 cover the theory of the neutron-, proton-, and alpha-induced nuclear reactions. Chapters 11, 12, and 13 deal with the spontaneous decay, the interaction with electromagnetic radiation, and the beta decay of the nuclei, respectively. The 14th chapter concludes the book with a discussion of the empirical evidence for a nuclear shell structure and its interpretation by the single particle model. The appendices A and B contain helpful information on special mathematical tools.

The book is certainly not written for theoretical nuclear physicists only. It is written in a language which almost throughout can be understood by any scientist working in a related field. Much previously unpublished information is included. It may well be expected that this book will serve as the standard work for many years.

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NOTES AND PERSONALIA

NOTES

Translations of Russian Scientific Literature--A co-operative plan for preparing translations of Russian scientific literature has been put into effect by the Department of Scientific and Industrial Research, Cunard Building, 15 Regent Street, London, S.W.1, Great Britain. A wide variety of journals is included in this service, and translations are made if two or more requests are received for the same paper. The cost is on a sliding scale per page, with the minimum charge for cases where nine or more requests have been received. Full details, with contents lists of the journals covered, are contained in the monthly Translated Contents Lists of Russian Periodicals, published by H.M. Stationery Office, P.O. Box 569, London, S.E. 1.

Many employment opportunities for civilian scientists and technologists in the Air Force--A new publication, "Careers for Civilians," outlines many available positions for civilians in many kinds of scientific and technological work in most all parts of the country, describing opportunities in general. Interested persons may secure further information by writing to Director of Civilian Personnel, Headquarters, U. S. Air Force, Attn: Placement and Employee Relations Division, Washington 25, D. C., requesting the above booklet.

Opportunities for employment for scientists and technologists in activities of the Navy--The Scientific Personnel Employment Bulletin for January 1953, issued by the Office of Naval Research, outlines numerous positions available to scientists and technologists in many fields and in various parts of the country. Interested persons should write for a copy of the Bulletin to the Office of Naval Research, Washington 25, D. C.

Fellowships and assistantships in the Department of Meteorology and Oceanography at New York University--Two fellowships in meteorology or oceanography and several assistantships on sponsored research projects are available for the academic year 1953-54. Applications should be completed by April 1. Further information may be secured from Assistant Dean in Charge of the Graduate Division, College of Engineering, New York University, New York 53, N. Y.

Scholarships, fellowships and graduate assistantships at Lehigh University--Lehigh University announces the availability of various types of graduate appointments in several fields of science and technology for the academic year 1953-54. Applications should be submitted by March 1. Awards will be made by April 1. Inquiries should be addressed to the Admissions Office or to the Head of the Department concerned at the University at Bethlehem, Pa.

Illustrative material relating to careers in geophysics and geochemistry available for loan--Pennsylvania State College announces the availability, on loan, of a set of Kodachrome slides illustrating a career in geophysics and geochemistry, intended for use in high schools in guidance work. Eleven other sets covering various fields of the mineral industries are being prepared. Arrangements for loan should be made through the Division of Geophysics and Geochemistry, Mineral Sciences Bldg., Pennsylvania State College, State College, Pa.

Navy oceanographic laboratory to be built at Woods Hole, Mass.--Plans for the construction of an oceanographic laboratory at Woods Hole, Massachusetts, were recently announced by the Navy. The new building will be Navy-owned, but contract operated. Construction of the modern, three-story, concrete-frame, brick-faced building, with a floor space of 26,000 square feet, will begin shortly.

World production of petroleum--The world production of petroleum in 1952 was about four and a half billion barrels of which almost two billion, three hundred million barrels or slightly over fifty per cent were produced in the United States. Both world production and production in the United States were at all-time high, but the percentage production in the United States has steadily decreased from a high of 67 per cent in 1943. About 46,800 new wells were drilled in the United States in 1952 of which about 24,000 produced oil, over 3000 only gas, and almost 18,000 were non-producers.

Index to geological mapping in Alaska--The U. S. Geological Survey announces the availability of an index map of geological mapping in Alaska, free upon request to the Information Officer of the Survey, Washington, D. C., or to the offices of the Survey in San Francisco, Calif., or Fairbanks or Juneau, Alaska.

Revised maps of the Mississippi River Commission--The Commission announces the availability of two revised quadrangles, scale 1:62,500, relating to areas in the Arkansas-Tennessee area, these showing the up-to-date levee, revetment and dike systems, and the early river meander lines. Inquiries should be addressed to the Commission in Vicksburg, Mississippi.

Meeting of U. S. National Committee of URSI and the IRE antenna group--The meeting of the United States National Committee of the International Scientific Radio Union and the Professional Group on Antennas and Propagation of the Institute of Radio Engineers will be held at the National Bureau of Standards April 27-30, 1953. Interested persons should write to the Secretary, Dr. A. H. Waynick, Pennsylvania State College, State College, Pa.

Anthracite Conference at Lehigh University--The Eleventh Annual Anthracite Conference will be held at Lehigh University on May 7-8, 1953 under the joint sponsorship of the University and the Anthracite Institute. It will be concerned with the latest developments in the distribution, utilization, economic and hygienic aspects of anthracite coal.

Course in photogrammetry in Paris--A course on the theory and practice of aerial photography and photogrammetry is to be given in Paris from June 22 to July 31, 1953 under the auspices of the National Geographic Institute. Interested persons may secure more information by addressing: Le Directeur de l'Ecole Nationale des Sciences Géographiques, 35, Boulevard des Invalides, Paris 7, France.

New courses in Geology at American University--A complete sequence of courses in professional geology is now being offered at American University. These include Historical Geology, Economic Geology, Stratigraphy, and Mineralogy and Petrology. These courses are given in the evening. Further information may be secured from the Director of Geology, American University, Massachusetts and Nebraska Avenues, Washington, D. C.

International Commission on Irrigation and Drainage--This Commission met recently and accepted the United States as a new member. Seventeen countries were represented. The next meeting of the Commission will be held in April 1954 in Algiers. Walter E. Blomgren has been designated as Chairman of the U. S. National Committee, with G. T. McCarthy and Harold Conkling among the members.

New Director of American Geological Institute--The American Geological Institute announces the appointment of Robert W. Webb as Executive Director of the American Geological Institute. He will serve also as Executive Secretary of the Division of Geology and Geography of the National Research Council. He is on leave from his position as Professor of Geology of Santa Barbara College.

Fourth Congress of the International Association on Quaternary Research--The Fourth Congress of the Association Internationale pour l'Etude du Quaternaire (INQUA) will be held in Rome and Pisa, Italy, August 10 to September 10, 1953. Interested persons should write to the Secrétariat Général, Istituto di Geologia, Via S. Maria 31, Pisa, Italy.

PERSONALIA

Z. Frankenberger of Climax, Michigan, has taken up duties in the Department of Gravimetry of the Gulf Research and Development Co. in Pittsburgh.

E. J. Gumbel, has been appointed Visiting Professor for Mathematical Statistics by the Free (West) University of Berlin for the summer term of 1953.

William C. Gussow has opened a consulting office as Geologist Engineer in Calgary, Alberta, Canada.

Koji Hidaka of the Geophysical Institute of Tokyo University, is devoting the academic year to work in the Department of Oceanography at the Agricultural and Mechanical College of Texas.

Harold L. James is on leave from his duties with the U. S. Geological Survey and is serving as Visiting Lecturer in Geology at Northwestern University during the winter and spring quarters of the current year. He is teaching and directing graduate research in Petrology and Ore Deposits.

Don Kirkham, Professor of Soils and Physics at Iowa State College was given the Stevenson Award at the Annual Meeting of 1952 of the Soil Science Society of America. The Award carries a citation and a stipend of $500.

Frederic T. Mavis, Head of the Department of Civil Engineering at Carnegie Institute of Technology, has been elected President of the Pittsburgh Section of the American Society of Civil Engineers.

DeWitt C. Van Siclen, Captain with the Air Force Research and Development Command in Baltimore, has returned to civilian life and has taken up duties as Senior Geologist with the Pan American Production Co. with headquarters in Houston.

H. B. Peacock, until recently with Geophysical Services, Incorporated, with headquarters in Dallas, Texas, has sold his interest in the company to enter the geophysical exploration field as a consultant.

Thorndike Saville, Dean of the College of Engineering, New York University, recently headed a delegation from the United States to England for an international conference on engineering education.

Edward J. Schaefer, until recently District Engineer for the U. S. Geological Survey with headquarters in Columbus, Ohio, has left that work to establish a consulting practice on groundwater problems with headquarters in Columbus.

R. F. A. Studds, Rear Admiral, and Director of the U. S. Coast and Geodetic Survey, has been awarded the Exceptional Service Gold Medal of the Department of Commerce for his many years of service in the Survey and his outstanding leadership as its Director.

Howell Williams, Professor of Geology at the University of California at Berkeley, will deliver the William Smith Lecture to the Geological Society of London.

E. W. K. Andrau, of Alief, Texas, Consulting Engineer on development of petroleum, was killed in an airplane accident September 20, 1951 at the age of 51. He was born in Sumatra, studied at the University of Zurich and the University of Lausanne, receiving his doctorate from the latter in 1925. He worked on geophysical exploration problems in Iraq until 1928, and then spent a year in the Roumanian oilfields. In 1929, he came to the United States, working on exploration and development problems for the Shell Oil Company until 1934. Since 1934, he had operated in his own name. He had been a member of AGU since 1947.

Monroe George Cheney, President of Anzac Oil Corporation of Coleman, Texas, died September 28, 1952. He was born at Franklinville, N. Y., September 27, 1893. He took his baccalaureate degree from Cornell University in 1916, and in 1919 studied at the Royal School of Mines in London. His early career was devoted to geological work for various gas and oil operators, and in 1919 he established himself as a consulting geologist with his own operating oil company. He had been a member of AGU since 1943.

Gilbert D. Harris, Treasurer of the Paleontological Research Institution (which he founded in 1932) at Ithaca, N. Y., died December 4, 1952 at the age of 88. He was born in Jamestown, N. Y. He received his baccalaureate degree from Cornell University in 1886. He began his professional career on geological work for the Arkansas Geological Survey, taking up duties with the U. S. Geological Survey in 1888. In 1892, he joined the staff of the Texas Geological Survey, returning to Cornell in 1894, where he served until he retired as Emeritus Professor in 1935. He served, also, as State Geologist of Louisiana from 1898 to 1909. He had been a member of AGU since 1947.

William Herbert Hobbs, Emeritus Professor of Geology, University of Michigan, died January 1, 1953 at the age of 88. He was born in Worcester, Massachusetts, and received his baccalaureate degree from Worcester Polytechnic Institute in 1883. He took his master's degree and doctorate from Johns Hopkins University in 1888, and attended Heidelberg University in 1889. He was the recipient of a number of honorary degrees. His professional career began with an instructorship at the University of Wisconsin in 1889, where he progressed to a professorship before he went to the University of Michigan in 1906. He became Emeritus Professor in 1934. Many special tasks and honors came to Professor Hobbs in his long career, including an exchange professorship with the University of Delft, the directorship of the University of Michigan's Greenland Expeditions in the late 20's, the editorship of the Journal of Geology, and offices in various of the scientific societies of which he was a member. He had been a member of AGU since 1931.

Thomas Augustus Jaggar, world-renowned volcanologist, died in Hawaii January 17, 1953. He was born in 1871, took his baccalaureate from Harvard in 1893, his master's degree in 1894, and his doctorate in 1897. In addition, he was the recipient of a number of honorary doctorates. His professional career was long and varied, beginning with an instructorship at Harvard in 1895, where he remained until 1906, working at the same time for a part of this interval for the U. S. Geological Survey. He then became Professor of Geology at Massachusetts Institute of Technology where he remained until 1917. He established the Hawaiian Volcano Observatory in 1912, and served as its director until 1919. From 1919 to 1940, he served the U. S. Weather Bureau, the U. S. Geological Survey, and the National Park Service with headquarters in Hawaii. Since 1940, when he officially retired, he has been a Research Associate of the University of Hawaii, continuing his study of volcanoes. He is the author of a number of books and many scientific papers, took part in various volcanological expeditions, notably to Martinique, the Aleutians, and Japan, and has received honors and awards for his outstanding scientific contributions. He had been a member of AGU since 1922, serving as Vice President of the Section of Volcanology from 1922 to 1924, and President from 1924 to 1929.

Forest Ray Moulton, who retired in 1949 as Administrative Secretary of the American Association for the Advancement of Science, died December 7, 1952 at the age of 80. He was born at LeRoy, Michigan, and received his baccalaureate degree from Albion College in 1894. He was awarded a number of honorary doctorates. He began his professional career at the University of Chicago, advancing to a full professorship in 1912. He left the University of Chicago in 1926 to take up duties as Director of Utilities Power and Light Corporation where he served until 1937, when he took up duties with the AAAS. He served on many important committees and commissions, notably in his own special field, astronomy, but in other fields as well. He had been a member of AGU since 1921.

Walter Riddell, geophysicist with Acme Geophysics Exploration, Ltd., of Canada, died suddenly on August 17, 1952, at the age of 57. He was born in Arden, Manitoba. He took his baccalaureate degree from the Polytechnic College of Oakland, California in 1921, and another from New Mexico School of Mines in 1931. He subsequently did graduate work at that same school and at Colorado School of Mines, and was actively engaged on geophysical exploration since 1933, beginning with the Acme organization in 1934. He became a member of AGU in 1951.

Joseph Audley Sharpe, Vice President of the Frost Geophysical Corporation, died suddenly on May 9, 1952 at the age of 45. He was born at Axtell, Kansas, but was brought up in Arizona. He took his baccalaureate degree from the University of Arizona in 1928, where he continued as an instructor until 1930. After a two-year assistantship at the University of Wisconsin, he entered Massachusetts Institute of Technology where he received his doctorate in 1934. He entered the service of Western Geophysical Company, and in 1937 became Chief Physicist of the Stanolind Oil and Gas Co. In 1945, he took up duties with the Frost Geophysical Company, serving as Executive Vice President, and at the same time, President of the Frost Airborne Survey Corp. He had been a member of AGU since 1934.

Francesco Vercelli, of the Istituto Talassografico in Trieste, died November 24, 1952.

Fayette S. Warner, Engineer-Economist with the Federal Power Commission, died January 23, 1953 at the age of 59. He was born at Sunderland, Massachusetts. In 1921, he received his baccalaureate degree from Rensselaer Polytechnic Institute. From 1922 to 1930 he held a professorship at Wharton School of Finance of the University of Pennsylvania, engaging in public utilities and industrial research, and taking a degree in business administration. He received his doctorate at the University of Pennsylvania in 1929. From 1930 to 1933 he worked with E. T. Cheney as an engineer on the valuation of utilities. He had been with the Federal Power Commission since 1933. He became a member of AGU in 1946.

UNION, SECTION, AND COMMITTEE ACTIVITIES

Report of Representatives on Council of American Association for the Advancement of Science--J. P. Marble attended the meetings of this body on December 27th and 30th, 1952. The business transacted was of a routine nature, none of which affected the relations of the two organizations. Extensive revisions to the Association constitution and by-laws were put into effect, but those portions governing the relation of affiliated societies remain unchanged. The proceedings of the meetings will be published in Science and Scientific Monthly in due course. An appeal was made to obtain a more representative selection of papers for Science, which at present carries papers chiefly in the fields of biology and medicine. Persons desiring to obtain reasonably prompt (not over six months) publication of short papers or notes in the various fields of geophysics will receive interested attention from the Science editorial staff.

Your delegate could not attend the first of the two meetings in geophysics, because of conflict with the second Council meeting. The program, which included seven papers on various aspects of geophysics was completed too late for inclusion in the printed program. Attendance was about 25. The afternoon session was better attended; about 65 were present.

John Putnam Marble

SPECIAL ANNOUNCEMENTS

Thirty-Fourth Annual Meeting, Washington, D. C., May 4-6, 1953--Attention is called to previous announcements in the Transactions (Oct. 1952, p. 794; Dec. 1952, p. 944) concerning the Thirty-Fourth Annual Meeting of AGU to be held in Washington, D. C., May 4-6, 1953. Three copies of the titles and abstracts of papers are to be in not later than March 10, 1953, with word concerning time desired (ten to 20 minutes usually allowed) and projection equipment needed. Programs may be closed in advance of March 10 if they are filled. The information may be sent to the office of AGU or to the Section Secretary or Program Chairman as shown in the October announcement. The December announcement gives information regarding hotel reservations.

Regional Meeting in Minneapolis, Minn., August 31, 1953--As noted in the December 1952 issue of the Transactions, page 945, a meeting of AGU will be held in Minneapolis on August 31, 1953 just prior to the meeting of the International Association for Hydraulic Research and the Division of Hydraulics of the American Society of Civil Engineers. Plans for the program are developing. Interested persons should get in touch with Chairman Martin E. Nelson, U. S. Engineer Office, Post Office Bldg., St. Paul 1, Minn., or Secretary Roy F. Warner, 1872 N. Howard St., St. Paul 9, Minn.

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TRANSACTIONS
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MICROSEISMS, MICROBAROMS, STORMS, AND WAVES IN WESTERN NORTH AMERICA

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(California Institute of Technology, Division of the Earth Sciences
Contribution No. 596, Pasadena, California)

Abstract--Microseisms with periods from five to eight seconds recorded by long-period instruments at stations near the Pacific coast from November 29, 1951 to January 4, 1952 are discussed in their relation to meteorological conditions, ocean waves, and microbaroms.

Introduction and material used--In spite of hundreds of papers on the four to ten-second period microseisms there is still general disagreement concerning their cause, velocity and wave type. Some of the instruments at Palomar [see, for example, BENIOFF, GUTENBERG, and RICHTER, 1951, p. 752], which are being installed under the sponsorship of the Geophysics Research Division of the Air Force Cambridge Research Center, are in operation. To aid in the interpretation of their records a study was undertaken of microseismic storms in California occuring between November 24, 1951 and January 4, 1952. Microseismic records at Pasadena, Palomar, and Tinemaha (California Institute of Technology), at Ukiah and Tucson (U. S. Coast and Geodetic Survey), at Victoria, British Columbia (Dominion Observatory), and at Santa Clara (University of Santa Clara) were taken for the whole interval and, in addition, records of Berkeley (University of California), Tacubaya (Mexico), China Lake (California Institute of Technology), and Seattle (University of Washington) for the interval November 24 to December 7. Data on the instruments are summarized in Table 1.

Table 1--Approximate constants of instruments; T = period of pendulum, Tg = period of galvanometer, Vm = maximum magnification, V6 = magnification for continuous waves of six-second period

Station	Instrument	Component	T	Tg	Vm	V6
			sec	sec		
Berkeley	Galitzin	Z	12	12	1000	1000
China Lake	Benioff (film)	Z	1	90	10000[a]	4000[a]
Palomar	Benioff	Z	1	14	30000	6000
Pasadena	Benioff	Z	1	14	10000	2000
Pasadena	Benioff	Z,H	1	120	2000	600
Pasadena	Wood-Anderson	H	6	...	800	600
Santa Clara	Galitzin	H	12	12	1000	1000
Seattle	Sprengnether	H	6	8	2000	1600
Tacubaya	Wiechert 17-ton	H	1 1/2	...	2000	100
Tinemaha	Benioff	Z	1	90	1000	400
Tinemaha	Benioff	N-S	1	90	2000	800
Tucson	Benioff	Z	1	77	5000	2000
Ukiah	McComb-Romberg	H	12	...	75	70
Victoria	Milne-Shaw	H	12	...	250	250

[a] If film is measured on screen with 8× magnification.

At Berkeley, Pasadena, and Seattle, instrumental constants were determined during the latter part of 1951. For the other stations listed in Table 1 magnifications were based on earlier or approximate determinations. However, the data for T and Tg are probably nearly correct for all stations.

Double-trace amplitudes of the microseisms (between maxima and minima) and corresponding periods were measured, and the averages of the five largest amplitudes within about ten minutes were tabulated. For the first twelve days, readings were made for all even hours, on the remaining records only for 00h, 06h, 12h, and 18h unless there was an appreciable change in amplitudes.

Data for the weather conditions were taken from the maps issued daily for 04h 30m, 10h 30m, 16h 30m and 22h 30m PST by the U. S. Weather Bureau Forecast Center at the Los Angeles Airport

(A. K. Showalter in charge; R. D. Graham, Research Forecaster), which also made available additional information on the hurricane on November 27-30. Some information for the first six days was taken from the Cartas del Tiempo of the Servicio Meteorologico Mexicano, which were furnished by R. Lopez, and some data were added from the Daily Weather Maps of the U. S. Weather Bureau published at Washington, D. C.

Data on breaker heights at La Jolla were transmitted by R. S. Arthur of the Scripps Institution of Oceanography, La Jolla, California. They are the average heights (trough to crest) of the higher waves in groups of breakers and were estimated at about 08h PST by D. B. Sayner of the Scripps Institution of Oceanography.

Data on deep water waves and breakers at the Surf and Weather Station (L. G. Boyd in charge) of the U. S. Marine Corps, Camp Pendleton, near Oceanside, California, were furnished by Oliver P. Smith through W. S. Brown, Acting Chief of Staff. The station operates a Mark IX Shore Wave Recorder with a pressure head in 35 ft of water, approximately 2500 ft offshore. At about 04h, 10h, 16h, and 22h PST the speed of the recorder is increased for 20 minutes to 1.7 mm/sec. Visual observations of breakers are made approximately at 06h, 10h, and 16h PST. For both series the average height in feet (from trough to crest) of the highest one-third of all waves was given for each day with the corresponding average period, also the amplitude of the highest visually observed wave, and the amplitude and time of the highest recorded wave regardless of recording speed.

R. L. Wiegel, Project Engineer of the Waves Research Laboratory, Institute of Engineering Research, University of California, supplied data on wave heights from records of their Mark IX wave recorder at the end of the Signal Oil and Gas Company pier at Ellwood, California, about ten miles west of Santa Barbara. On most days four high-speed records were taken, each covering about 20 minutes, and for each the wave periods and the average height of the highest one-third of the waves, as well as the maximum wave height in feet (from trough to crest), were listed.

The wave data of the three stations proved to be very valuable and the author is grateful to all who aided in their preparation and transmission for the present research.

Types of microseisms--Forty years of investigations of microseisms throughout the world by instruments with different characteristics have led to the conclusion that, in addition to microseisms from tropical disturbances and those from strong monsoon over the ocean and similar winds, there are at least two types having periods between four and ten seconds. The type discussed in the present paper consists of more or less regular waves with periods most frequently between five and seven seconds. During microseismic storms, periods of eight to nine seconds have been observed in North America [GUTENBERG, 1931, p. 13] and periods up to over ten seconds in Eurasia at greater distance from the source [see, for example, GUTENBERG, 1932, p. 282]; on the other hand, these regular microseisms may have periods as short as three or four seconds if the amplitudes are very small, especially during the summer months, but rarely, if ever, during "microseismic storms."

The type of microseisms sometimes confused with the preceding, appears to be observed mainly near coasts and exhibits prevailing periods of four to five seconds even when amplitudes are large; the waves are usually somewhat irregular. Contrasting with the regular type, the amplitudes sometimes increase by a factor of three or more within less than one hour, especially if strong winds follow the passage of cold fronts near the station.

The two types of microseisms frequently occur simultaneously, but their maxima are usually at different hours or even on different days.

General data on the observed regular microseisms with periods from five to eight seconds--Since for most of the instruments listed in Table 1 the magnification is only roughly known, the following calculated maxima of the ground amplitudes during the respective periods under investigation are approximate only: at Pasadena (on November 29) horizontal and vertical components three to four microns; at Tinemaha (November 29) N-S and vertical components probably two to three microns; at Seattle (records at Seattle on December 18, when at Victoria amplitudes were about 25 pct higher than on December 4, were not included in the investigation), Ukiah, and Santa Clara (December 4-5) horizontal component about six or seven microns; at Victoria (December 18) horizontal component about 15 microns; at Berkeley (December 5) vertical component five microns; at Tucson, vertical component about 2 1/2 microns (November 28-29); at Tacubaya horizontal component about three microns (November 27). On November 25 and from December 1-6 the records at Tacubaya do not show noticeable microseisms with periods over one second, which fact indicates that their ground amplitudes were probably less than one micron. Microseisms measured on the records for Victoria (drum speed eight mm per minute) may have been entered in one or the other instance in Figures 2-7, although the microseisms may have been of the type having periods of four seconds.

As cited earlier, the periods of the microseisms discussed here were usually between five and seven seconds (Figure 1), but occasionally they dropped to four seconds on days with small microseisms (for example, Tucson, November 25). They reached eight seconds, for example, at Berkeley, Ukiah, and Tucson on December 4-5, and at Palomar December 20. At most stations the longest periods were recorded at times of relatively large amplitudes, as usual. On a few records of the Benioff instruments with Tg = 14 seconds and on some of the Sprengnether instruments "wind microseisms" were so large that it was difficult to measure the regular microseisms. Records of some short-period instruments on such days showed waves with periods of three to five seconds that crisscrossed several lines.

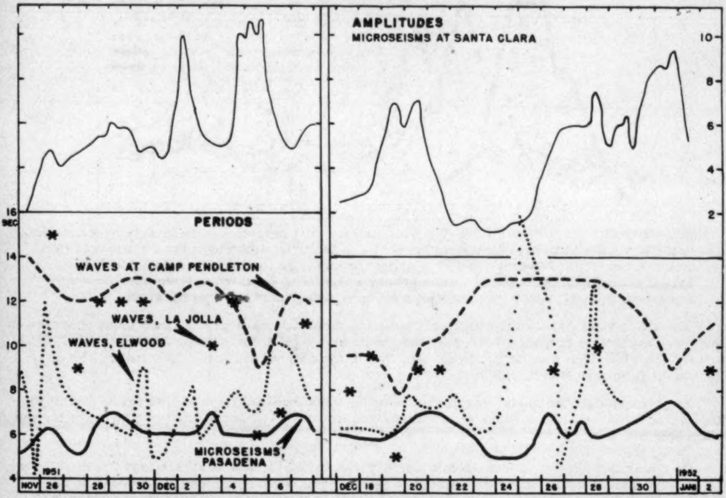

Fig. 1--Amplitudes and periods of microseisms and amplitudes of ocean waves

For comparison of the microseismic amplitudes on maps it was considered best to express for each station all observed trace amplitudes in per cent of the largest measured trace amplitude (most were on November 27-29 or on December 4-5; see Fig. 2 and 3). This procedure is similar to the method used by the author in earlier research [see, for example, GUTENBERG, 1932, p. 282] where advantages and disadvantages of this procedure are discussed. The effect of the relatively small changes in period on the calculated ground amplitudes is within the limits of error in most instances and was considered when necessary. The curves for the trace amplitudes (Fig. 2) at Seattle and Victoria are similar, and also those for Santa Clara and Berkeley, though all four have different types of instruments.

Comparison of microseismic activity, meteorological conditions, and ocean waves--Trace amplitudes of the microseisms were plotted for November 25, 1951 to January 4, 1952. Figures 2 and 3 show selected and somewhat smoothed curves. The units of the vertical scale are arbitrary and differ from station to station. Also included in Figures 2 and 3 are all available data on the heights of breakers at the Scripps Institution of Oceanography at La Jolla, California.

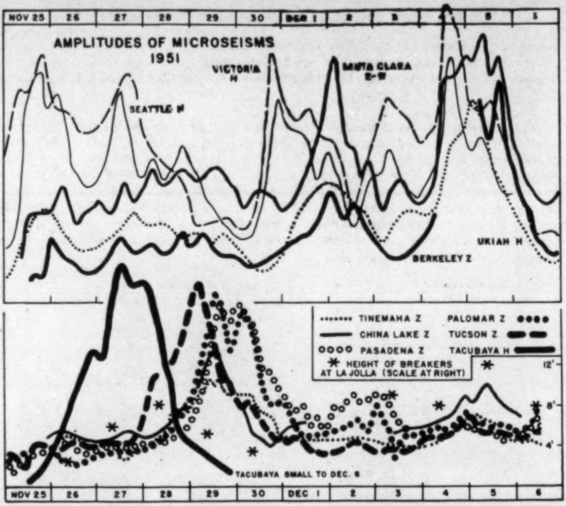

Fig. 2--Relative amplitudes of regular microseisms with periods of five to seven seconds in arbitrary units (different for most curves) for selected stations near the Pacific coast of North America, and average height of higher breakers in feet (double amplitudes), estimated at Scripps Institution of Oceanography at La Jolla, California; November 28 - December 7, 1951; upper part, northern stations; lower part, southern stations

The differences between the times of maximum amplitudes are greater than those observed in microseismic waves crossing Europe or the United States [see, for example, GUTENBERG, 1951, p. 1309, Fig. 5]. This may be due to the fact that in the present study the stations are closer to the source [compare BÅTH, 1950b].

For a more detailed study, weather maps of the area involved were plotted (examples in Figures 4-7). Times for the weather observations are usually 1 1/2 hours earlier than those for the microseismic data.

On November 25, 00h, microseismic activity was relatively low at all stations involved. During the day microseisms increased rapidly at Seattle and Victoria and less pronounced at other stations, probably in connection with a storm over the northwest Pacific with strong winds off British Columbia. The winds there decreased on November 26 and did not change much during the following days (Fig. 4). The outstanding phenomenon during the period November 26 to 30 is the "microseismic storm" at the southern stations (Fig. 2), which were in an area of relatively high pressure and rather small wind velocities. However, a hurricane existed off the tip of Lower California with the locations of the center, and minimum pressures in millibar, at 04h 30m PST, as shown in Table 2. The maximum of the microseisms moved northward from Tacubaya on November 27-28 to the Southern California stations on November 29. At least as far north as Tinemaha, the microseismic amplitudes reached larger values during this storm than on any other day of the whole period under investigation. On the other hand, there is no corresponding increase in microseisms at the northern stations, especially at Santa Clara and Berkeley, which both were at about the same distance from the hurricane as Tinemaha. Apparently along the paths following the geologically inhomogenous coastal zone (Fig. 8), the microseismic waves suffered a much greater loss of energy than along the paths farther inland. Similar loss of energy has been found repeatedly since 1914 in Europe for microseisms, especially those traveling from north to south and crossing the structural boundaries [GUTENBERG, 1951, p. 1308, esp. Fig. 4; CARDER, 1952].

The relatively large differences in the times when the largest amplitudes were recorded at the different stations (Fig. 2) are similar to those found by GILMORE [1946] in the Caribbean

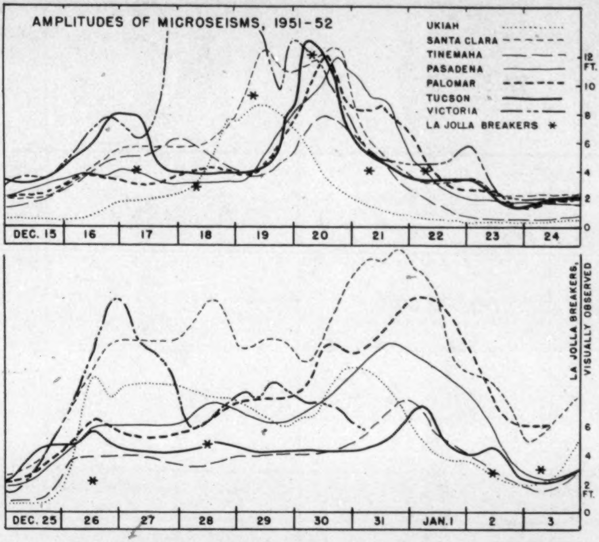

Fig. 3--Relative amplitudes of regular microseisms with periods of five to seven seconds in arbitrary units (different for most curves) for selected stations near the Pacific coast of North America, and average height of higher breakers in feet (double amplitudes), estimated at Scripps Institution of Oceanography at La Jolla, California; December 15, 1951-January 3, 1952; upper part, northern stations; lower part, southern stations

network of microseismic stations of the U. S. Navy in connection with hurricanes and may be partly a consequence of the fact that the energy of hurricanes is much more concentrated in a small area than that of nontropical storms. It is noteworthy that in Southern California the microseisms were still relatively large on November 30 (Fig. 4), when the hurricane was disintegrating rapidly.

Table 2--Location and minimum pressure of hurricane at 04h 30m on successive days, November 27-30, 1951

Date	Location		Minimum pressure
	N. Lat.	W. Long.	
	°	°	mb
Nov. 27	14	104	984
Nov. 28	16 1/2	107 1/2	982
Nov. 29	19 1/2	109	995
Nov. 30	24	109	1007

At La Jolla the breakers increased from November 26 to 28. Since the waves probably came from the south and, according to Robert S. Arthur (private communication) the exposure to southerly waves is relatively poor at the point of observation, the actual wave height may have been higher than is indicated by the breakers (maximum eight feet). The hour at which the highest breakers occurred is not known since observations are made only about 08h. The highest waves (15 ft) at Ellwood were recorded during the morning of November 28. The largest microseisms at Tucson occurred during the following night. At 08h, November 29, the breakers at La Jolla had decreased to 5 1/2 feet, but the maximum of the microseisms at Palomar (39 mi from La Jolla) and the other Southern California stations was reached about noon of that day. During the following day, waves and breakers (Fig. 9) as well as the microseisms decreased. At Camp Pendleton the increase in wave heights during

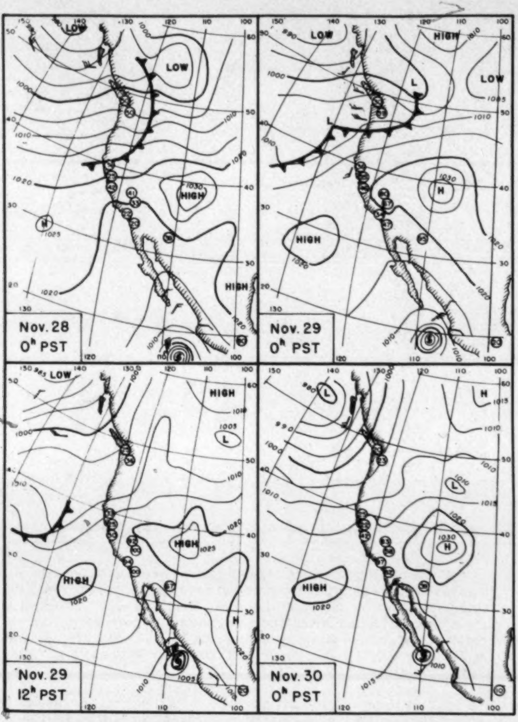

Fig. 4--Surface meteorological conditions and relative amplitudes of microseisms (in per cent of maximum for the respective stations), November 28-30, 1951

this period was relatively small, possibly due to refraction of the waves.

During December 1-2, 1951, microseismic activity had pronounced maxima at the northern stations. The low pressure area (960 mb off British Columbia on December 1, 00h) and cold front moved eastward, mainly across British Columbia, with rather strong winds (toward the coast on December 2, 00h). At Ellwood the wave heights reached 15 1/2 ft.

After a decrease on December 2-3 the microseisms at the northern stations increased rapidly and, except for Victoria, reached their largest amplitudes recorded during the respective periods under investigation on December 4 or 5. Meteorological conditions are reproduced in Fig. 5. Wind speeds ranged from 60 to 100 mi/hr along the Oregon coast on the afternoon of December 4, and all-time low pressures were recorded at several locations [U. S. WEATHER BUREAU, 1952]. Again, microseismic activity trailed meteorological activity. The increase and decrease of the microseismic amplitudes at the various stations (Fig. 2) is much more nearly coincident than in the case of the hurricane microseisms. There is, however, some indication on Figures 2 and 5 that the microseisms increased and decreased later in the south than in the north.

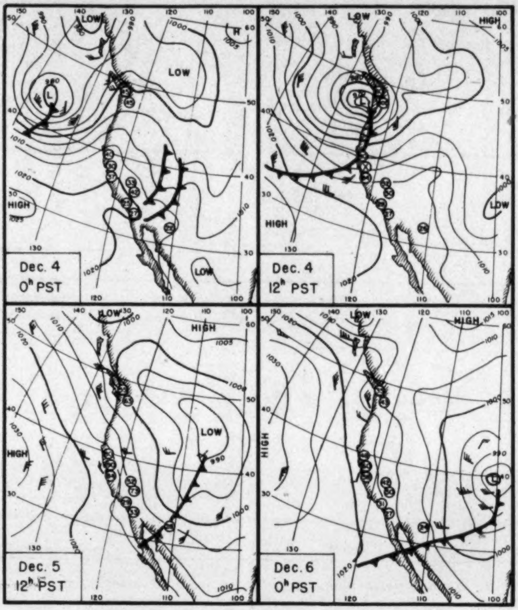

Fig. 5--Surface meteorological conditions and amplitudes of microseisms (units as in Fig. 4), December 4-6, 1951

Waves and breakers reached strong maxima (Fig. 9) at about the same time as the microseisms.

On December 7-8 microseismic amplitudes reached another maximum at the northern stations in connection with a deep low (975 mb) off British Columbia and southern Alaska. Between December 8 and 15, cyclonic and microseismic activity died down and the waves decreased. On December 17 a rather strong meteorological disturbance approached British Columbia. On December 18, 00h, its center was near Vancouver Island (Fig. 6). While on this day the microseisms at Victoria reached their largest amplitude for the five weeks under consideration (Fig. 3), microseisms at the southern stations, as well as the height of waves and breakers in Southern California (Fig. 9), increased only slowly. They reached a maximum December 20 (Fig. 6) when the center of the disturbance was far inland, but strong winds continued off the coast of California. The unusual report of "high NW swell" by a vessel in this region on the morning of December 20 is noteworthy as well as the fact that waves and breakers reached maxima on December 19-20 (Fig. 9). At the same time microseisms at the northern stations were decreasing rather rapidly. In Southern California waves and microseisms decreased rather slowly on December 21-22 (Fig. 6). Between December 18 and 23 there was again a delay of microseismic amplitudes relative to the time of maximum transfer of energy from the storm to the area considered, and a gradual southward shift of microseismic activity.

During December 23-24 the meteorological as well as the microseismic activity was low. On December 25 a storm approached the northern Pacific Coast (Fig. 7) which caused an increase in microseisms while the storm was rather far off the coast. The microseisms at the northern stations (Fig. 3) increased considerably on December 26; the southern stations showed a definite but more moderate increase. From December 28-30 (Fig. 7) microseisms increased slowly or remained about constant (Fig. 3), although on December 29 a well-developed storm center was

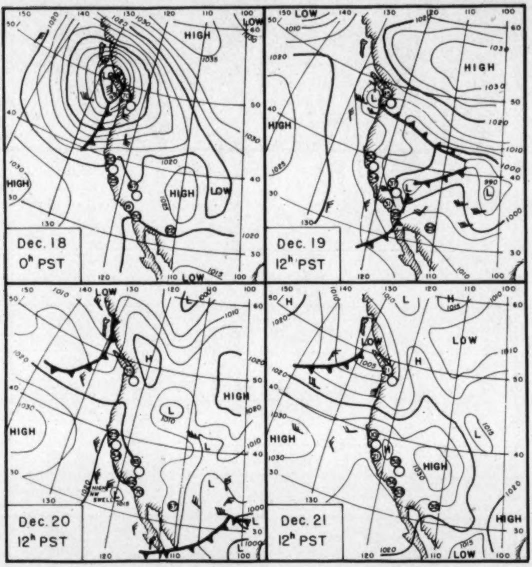

Fig. 6--Surface meteorological conditions and amplitudes of microseisms (units as in Fig. 4), December 18-21, 1951

near Vancouver Island. During December 30 the intensity of this disturbance decreased and a pressure trough developed eastward. During the morning of December 31 only a minor low-pressure center (1010 mb) remained at the coast near 45° N. The main storm center (990 mb) was about 1000 mi to the east of California in Colorado. Contrasting with the decrease in meteorological activity on December 30, the amplitudes of the microseisms in Southern California remained fairly high (about 50 pct of their maxima in November), and even increased to 80 or 90 pct on December 31 while the pressure differences decreased still further (Fig. 7). However, the ocean waves, as far as data are available, showed maxima on December 30-31 (Fig. 9) and reached over 15 ft at Ellwood on both days.

During this period the seismic activity again shifted southward to some extent, and there seems to have been a delay of at least two days between the time of the greatest meteorological activity near the coast and the largest microseisms in Southern California. On January 1, 1952 the latter decreased to or below 50 pct of their maxima in late November, during January 2 to about 30 pct, and to 25 pct or less in the early hours of January 3. On January 2 practically the whole area on the maps of Fig. 7 was covered by high pressure (maximum of about 1040 mb east of Vancouver Island, minimum of about 1000 mb north of the maps), and pressure gradients were small.

In all these microseismic storms, amplitudes of microseisms in Southern California attained their maximum about one or two days later than was to be expected from the meteorological conditions, for example, proximity of the storm center. Similar results have been found previously, by BÅTH [1949, pp. 112-118; 1950a, p. 354; 1951], KAMMER and DINGER [1951], and by VAN STRATEN [in press]. A discussion of the question how far breakers against a rocky coast or high waves in shallow water or other processes are responsible for microseisms, has not been attempted in this paper.

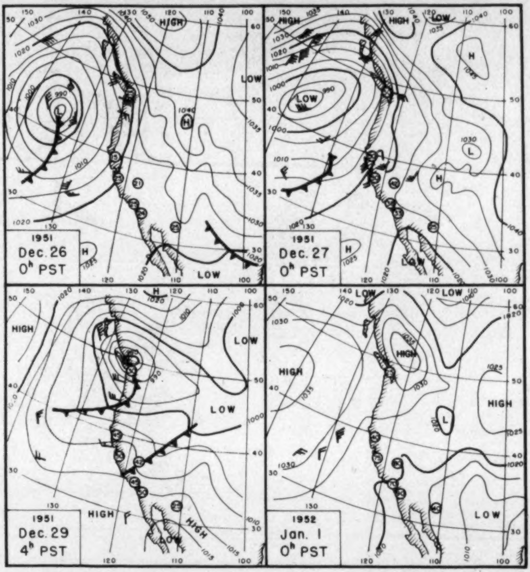

Fig. 7--Surface meteorological conditions and amplitudes of microseisms (units as in Fig. 4) December 26, 1951-January 1, 1952

There is a good correlation between amplitudes of microseisms and height of ocean waves. Especially the curves for microseisms at Santa Clara and the wave heights at Ellwood agree rather closely (Fig. 9). On the other hand, comparison of microseisms at the various stations and of the height of ocean waves or breakers at the three locations reveals marked differences in details within each group, even if one excludes the hurricane microseisms in November. Local conditions affect the propagation of ocean waves and produce appreciable differences in the observed wave heights along the coast with its changing contours and submarine topography, while the recorded microseisms depend on the geological structure along their paths and may be greatly reduced by large-scale irregularities. For these reasons comparison of microseisms at one station with wave records at one place may be misleading.

The fact that high waves and breakers in Southern California usually had their maxima at about the same time as the microseisms may be taken as indication that the delay relative to the meteorological activity results partly from the time needed by a storm to build up high waves in the coastal areas close to the seismic station. In this process, high waves coming from the storm center may play a role. But, in addition, in a storm moving across the Pacific coast into Oregon, Washington, or British Columbia, the fetch of strong northwesterly winds frequently extends as far south as Southern California a day or two after the storm has reached the coast and then creates high waves there which, according to TODD and WIEGEL [1952], may be more important than waves of larger amplitudes generated farther at sea. Finally, cold air masses seem to produce higher ocean waves than warm air [ROLL, 1952].

In all instances of large microseisms connected with non-tropical disturbances which are discussed here the wind was between on-shore and parallel to the coast.

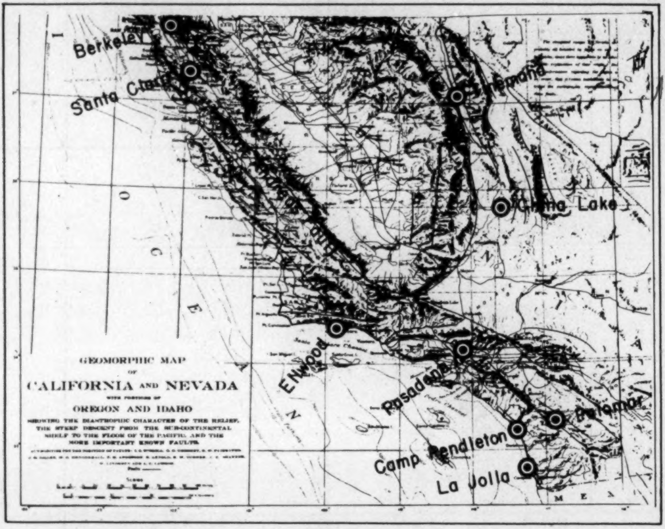
Berkeley
Santa Clara
Tinemaha
China Lake
ENwood
Pasadena
Palomar
Camp Pendleton
La Jolla
GEOMORPHIC MAP
OF
CALIFORNIA AND NEVADA
WITH PORTIONS OF
OREGON AND IDAHO
SHOWING THE DIASTROPHIC CHARACTER OF THE RELIEF, THE STEEP DESCENT FROM THE SUB-CONTINENTAL SHELF TO THE FLOOR OF THE PACIFIC AND THE MORE IMPORTANT KNOWN FAULTS
Scale

Fig. 8--Locations of seismic and oceanographic stations in California considered in the present paper; the base map was taken from Publication 87, of the Carnegie Institution of Washington [LAWSON and Others, 1908, map 1]

If a delay in development of ocean waves at the Atlantic Coast of America results there, too, in a lag of microseismic activity relative to meteorological conditions, it is more difficult to find it than on the Pacific Coast since the meteorological disturbances frequently increase in intensity as they move over the Atlantic Ocean away from the seismic stations near the Atlantic Coast. Incorrect conclusions can be expected if such a time lag is not considered.

Microbaroms and microseisms--Sinusoidal pressure waves in the atmosphere with periods of usually three to six seconds were designated as "microbaroms" by BENIOFF and GUTENBERG [1939]. By use of a tripartite station GUTENBERG and BENIOFF [1941] found that during the winter of 1940-41 the microbaroms at Pasadena arrived from the direction of the Pacific Ocean and were best developed when a "low-pressure area was situated off the coast of Southern California. As soon as the low-pressure area passed the coast, the microbaroms decreased rapidly." In Freiburg, Switzerland, they came prevailingly from NW [DESSAUER and Others, 1951]. For the period under investigation, amplitudes and periods of microbaroms were measured on film records written by Benioff microbarographs at Pasadena and Palomar.

At Pasadena the trace amplitudes (measured on the screen of a film projector) increased from 1/4 mm at 00h, November 25, to a maximum of 1 1/2 mm on November 26, 12h, then decreased to between 3/4 and 1 mm and did not change appreciably on November 29, when the microseisms reached their maximum. The microbaroms had maxima on December 2 (2 mm at 4h) and late on December 5 (1 1/2 mm). From December 10-14 a few times their trace amplitudes reached 1 1/2 mm; minor pressure disturbances existed off the coast of Southern California, but microseisms were small. On December 15 the microbaroms decreased and remained very small to December 20, while the microseisms increased (Fig. 3). On December 21, the microbaroms increased temporarily to about 1 mm. An increase, more or less parallel to the microseisms, started on December 25 with maxima of 1 1/2 mm on December 27. A rapid decrease followed, while the microseisms reached large amplitudes.

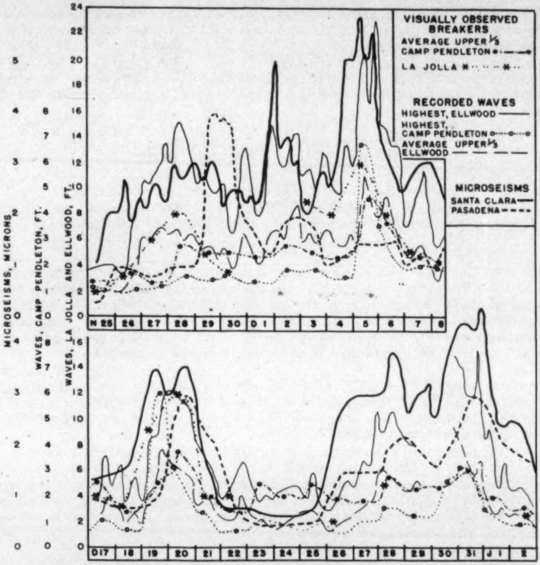

Fig. 9--Observed amplitudes of microseisms at Pasadena and Santa Clara in microns and of breakers and ocean waves (from trough to crest) in Southern California, November-December, 1951; connecting lines are for easier identification only and do not necessarily correspond to the actual changes

The microbaroms at Palomar changed relatively little from November 25 (trace amplitudes 1/4 to 1/2 mm) to November 27 (1/2 mm) and did not show a maximum on November 26, like those at Pasadena. They increased to a maximum of 1 mm during the afternoon of November 28 and had amplitudes of 1/2 to 1 mm on November 29 and 30. During the following days pressure effects of wind gusts at Palomar obliterated the microbaroms on the records. They showed maxima on December 12-13 (1 1/2 mm), on December 21 (1 mm), and on December 26-27 (2 mm), somewhat similar to the corresponding records at Pasadena.

The periods of the microbaroms were usually between three and five seconds. Periods of three seconds were observed only in connection with small amplitudes, periods of five seconds only on some days with relatively large amplitudes, especially at Pasadena on December 2, and 10-14, and at Pasadena and Palomar on December 26-27.

There is no close correlation between the microbarometric and microseismic storms in Southern California, although there is indication that both are connected with storms over the ocean [see also BAIRD and BANWELL, 1940]. DANIELS [1952] has suggested that the pressure changes in the air produced by ocean waves are large enough to serve as source of the regular microbaroms. For another type of atmospheric pressure waves which differ markedly from the microbaroms by their much shorter periods of 1/2 to 1 second, the "noise" of unusually large breakers at the nearby coast has been suggested as cause by BENIOFF and GUTENBERG [1939]. Since the microbaroms are pressure waves like the sound waves, they can be expected to show similar "zones of silence" and zones of strong perceptibility. Thus, microbaroms recorded at a station can be expected to originate mainly from given zones, changing with the vertical and horizontal distribution of temperature and wind, and it is probable that the sources of microseisms and microbaroms recorded at a given station are located far apart, even if they get their energy from the same storm system.

The periods of ocean waves, microseisms and microbaroms are of the same order of magnitude but differ in details as well as in range. In a storm area, average periods of ocean waves depend on the height about as follows:

Height of waves, m	2	5	10
Period, sec	6	8	10-12

At greater distance from the storm center these periods increase depending on the history of the waves [MUNK, 1951; TODD and WIEGEL, 1952, Table 4]. Ocean waves, as well as microseismic waves, grow longer while traveling. For other complications, see NEUMANN [1952] and ROLL [1952].

Figure 1 shows that there was no clear relationship between the periods of breakers and those of the microseisms. However, the periods of the breakers may differ appreciably from the wave periods in the area where the microseisms originated, and the periods of the microseisms may have increased between their source area and the stations where they were recorded. The amplitudes of the microseisms (Fig. 1) are usually largest when the periods of the ocean waves are smallest (that is, usually at times of strong winds off Southern California).

Summary and conclusions--Regular microseisms with periods of about six to eight seconds recorded at stations near the Pacific coast of North America during November-December, 1951 were investigated. The energy for a microseismic storm during the end of November was apparently furnished by a tropical disturbance off the tip of Lower California. Large microseismic activity during several intervals in December was related to non-tropical disturbances, usually approaching the coast north of California from the Pacific Ocean and then traveling inland. In all microseismic storms the increase and decrease of amplitude was delayed with increasing distance from the storm center. In Southern California the maximum amplitudes lagged behind such storm centers by about two days but usually coincided with the highest breakers and waves observed in Southern California. Microseisms traveling along the mountain chains and fault systems of the Pacific Coast decreased rather rapidly.

At Pasadena and Palomar there is no clear correlation between microseisms and microbaroms, but both seem to derive their energy from that of high ocean waves, probably at different distances from the respective stations.

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EARTH TIDES

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Abstract--The tidal variations of gravity have been observed throughout intervals of several weeks to several months at Los Angeles, Pasadena, Hawaii, and Attu. The term produced solely by the yielding of the Earth (including its oceans) may conveniently be characterized by two parameters. One parameter expresses the time-phase, the other the amplitude. In the most extensive and reliable series of observations, at Pasadena and Los Angeles, these parameters were found to be nearly constant in time. Geographically, however, the phase shifts differ greatly at widely separated stations. Knowledge of the phase and amplitude parameters (when constant) enables the classical harmonic tidal constituents to be easily computed. Computation of the gravity tidal constituents for the Pasadena and Los Angeles data were carried through by the proposed simplified method, and compared with corresponding results obtained with the standard U. S. Coast and Geodetic Survey and British Admiralty computational procedures. Satisfactory agreement was obtained among the three methods.

Observations of the tidal fluctuations of gravity at Los Angeles, Pasadena, Hawaii, and Attu are reported and discussed. These fluctuations [LOVE, 1911] are conveniently resolved into two components: (1) a major component due to the direct attraction of the Sun and Moon, and (2) a minor component arising from the tidal deformation of the Earth. The latter effect, which would vanish on a rigid planet, is the special subject of the present study. Let g(t) denote the time-variable part of the vertical component of gravity at a given observing station. This is the function directly determined by the gravimeter readings. At the corresponding position on a rigid Earth, let $g_o(t)$ represent the computed vertical component of acceleration due to the Sun and Moon. (The function $g_o(t)$ varies with position exceedingly slowly. A change of at least ten km in altitude, and generally much more laterally, is required to change $g_o(t)$ by one microgal. Hence in the present work there is no need for precise determinations of position. The "vertical" and "radial" directions may differ at the most by a fifth of a degree, that is, by the difference in the geographical and geocentric latitude of the observing station. The difference in the corresponding components of the tide producing acceleration is less than 2×10^{-3} microgals.) The difference, $g(t) - g_o(t)$, is the part arising from the deformation of the Earth which we desire to investigate. It is convenient to characterize this difference function, g(t), redundantly, by two time-dependent parameters -- a dimensionless amplitude factor, $\epsilon(t)$, and a time epoch, $\alpha(t)$. Thus

$$g(t) - g_o(t) \equiv D(t) = \epsilon(t)\, g_o\,[t - \alpha(t)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The convenience of this formulation arises chiefly from the fact that ϵ is found to be nearly constant in time at three of the four stations here reported, and α is apparently nearly constant in time at all four locations.

The observations--The total daily change in the function D(t) is only about 80 microgals. Thus for the satisfactory measurement and analysis of this function the ability to detect daily variations in gravity of the order of one microgal, or one part in a billion, is desirable. Such precision in gravity tidal observations, in so far as we are aware, has not yet been attained. The present measurements (excepting those at Attu which were greatly affected by microseisms) appear to be of unusually high quality, but they also leave much to be desired. Accordingly, our present effort is chiefly directed toward improving the precision of the observations rather than to the recording of more of the same at new locations, or to the treatment of the present measurements by more searching statistical procedures.

The current data have been obtained and processed as follows: The measurements of g(t) were made by photographing the scale and index of the gravimeter at ten-minute intervals, except at Attu where readings were taken at ten-second intervals in the effort to reduce the effect of microseisms. The negatives for the 29-day interval at Pasadena (about 4200 readings) were read in duplicate by two observers, with the aid of a standard microfilm reader. (We are much indebted to R. J. Ingram for reading these records, as well as for other valuable assistance to the project.) Comparison of these measurements indicates that the probable error in reading was of the order of five to ten microgals. The measurements at each station were plotted to a large scale, and hourly average readings were determined graphically by adjusting a smooth curve to the points. From the hourly averages so determined were subtracted the corresponding values of the computed function, $g_o(t)$, to form the "deformation function" D(t). (A simple method for computing the function $g_o(t)$ is being treated by J. T. Pettit in a separate paper, in press, entitled Tables for the Computation of Tidal Accelerations of the Sun and Moon.) A small linear correction, varying from zero to 1.5 micrograls per hour, was applied to remove a slow drift in the instrumental zero. (The respective drift corrections applied are indicated on Fig. 1 to 8.)

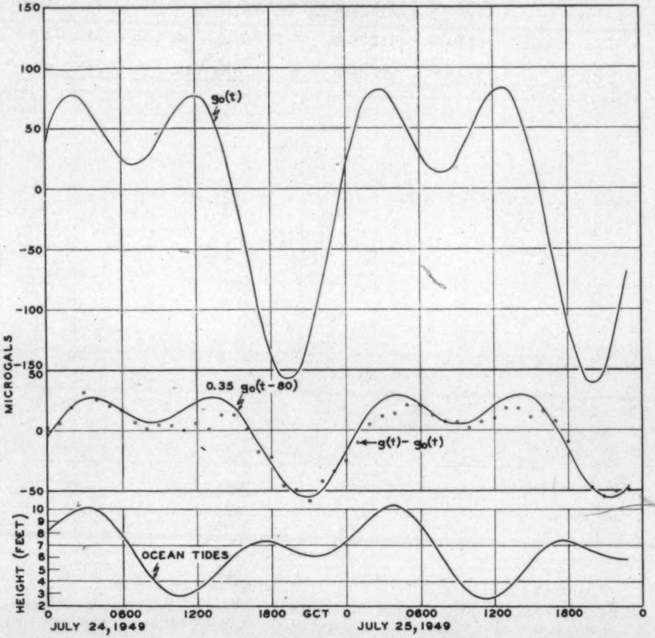

Fig. 1--Los Angeles Station, July 24-25, 1949; standard error of points with respect to indicated comparison function = 7.4 microgals; drift = 0.000 microgal per hour

The observations at Hawaii comprise a 36-day interval; at Pasadena, 29 days; at Los Angeles, 90 days. The voluminous data at Attu were processed for a selected 48-hour period. The precision of the measurements at Attu suffered greatly from the presence of microseisms. For this station only the large phase shift is regarded as reliable--the amplitude factor, ϵ, is subject to much uncertainty, as is indicated in Table 1.

In Figures 1 to 8 are shown typical results for intervals of two to six days at Pasadena, Los Angeles, and Hawaii. In the figures the top curve is the computed function, $g_o(t)$; the circled points represent the observational deformation function D(t) formed at hourly intervals as described; the middle curve is a comparison function of type $\epsilon g_o(t - \alpha)$, with ϵ and α constants at a given station. The lower curves represent the heights of the local ocean tides during the corresponding time intervals. In the case of the Los Angeles data, the phase α was determined by cross

Table 1--Values of ϵ and α

Station	Latitude	Longitude	ϵ	α in time	α in degrees
	° ′	° ′		min	
Attu	52 50 N	173 11 E	0.17 ± 0.20	210 ± 20	52 1/2 ± 5
Pasadena	34 09 N	118 10 W	0.32 ± 0.20	80 ± 20	20 ± 5
Los Angeles	34 04 N	118 26 W	0.35 ± 0.20	80 ± 20	20 ± 5
Hawaii	21 18 N	157 44 W	0.53 ± 0.20	180 ± 20	45 ± 5

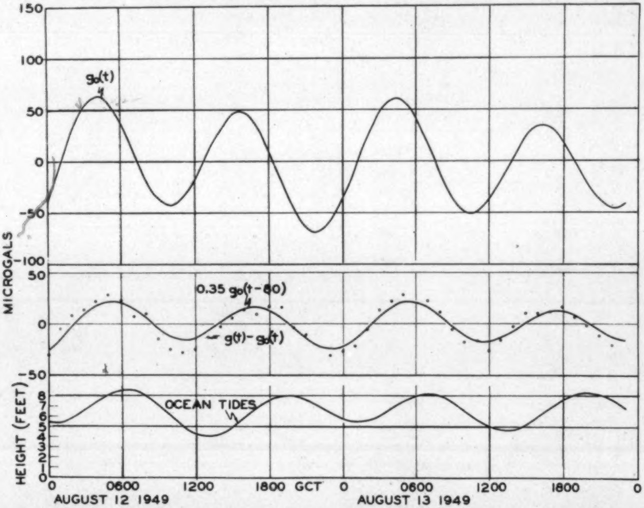

Fig. 2--Los Angeles Station, August 12-13, 1949; standard error of points with respect to indicated comparison function = 7.1 microgals; drift = 0.01693 microgal per hour

correlating the hourly averages for D(t) against $g_0(t)$ for a 48-day interval. The amplitude ϵ was then determined by making a least-square fit to D(t) throughout the same interval. Since the values so found did not differ significantly from those inferred from direct graphical comparisons, the evaluation of ϵ and α at the other three stations was accomplished by the more convenient graphical method. The data at Los Angeles were confirmed two years later (in 1951) by a run of ten days' duration with a different gravimeter. The previous values for ϵ and α (0.35 and 80 minutes, respectively) resulted, with estimates of the standard errors comparable to those for the previous observations. At a given station, the same comparison function has been adopted throughout the entire interval of observations; at the two California locations the same phase constant α resulted, and the amplitude factors differed only by ten per cent.

The difference between the adopted comparison function and the deformation function observed may be characterized by forming the standard deviation of the latter with respect to the former. At the California stations, these deviations are between 7.1 and 8.1 microgals in the four cases plotted (Fig. 1-4). In the case of the Hawaii data, the standard durations are between 5.8 and 12 microgals. Note that Figures 5, 6, and 7 present results for a continuous six-day interval;

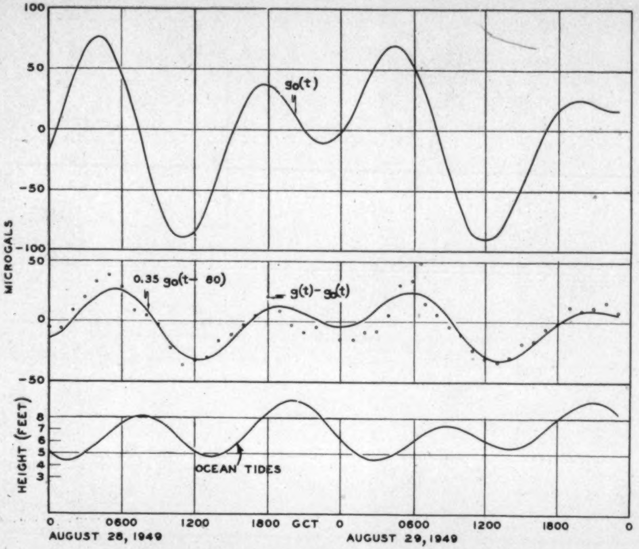

Fig. 3--Los Angeles Station, August 28-29, 1949; standard error of points with respect to indicated comparison function = 8.1 microgals; drift = 0.8323 microgal per hour

Figure 8 applies to a two-day sample, about a week later, in continuation of the same extensive run. In this figure, a systematic discrepancy both as to amplitude and phase is clearly apparent between the adopted comparison function and D(t). The satisfactory experimental investigation of such higher-order discrepancies appears to require, however, a higher order of reliability in the observational data.

The values for ϵ and α at the four stations, together with estimates of their standard errors, are listed in Table 1. The phase lags of 80 to 180 minutes are large; the difference in phase of 100 minutes between Hawaii and California is fivefold the estimated standard error of the phase determinations. This result appears to be explicable only on the basis that the general world-wide ocean tide is a large factor in the residual response. These large phase differences, as is pointed out in the following comparisons, tend to be overlooked in the customary methods of tidal analysis.

Comparison of methods of tidal analysis--The phase shift as here defined is the time lag of the deformation function D(t) with respect to the primary function $g_o(t)$. In the traditional procedures, however, it is the total variation, g(t), which is harmonically analyzed; consequently, the phase lags so determined are not the same quantities as those defined by us, and are, in fact, much smaller quantities. For example, in an harmonic analysis of our Hawaii data recently published [HOSKINSON, 1951], the phases of the two major constituents, M_2 and S_2, were 180° + 11.2° and 180° + 17°, respectively. The values 11.2° and 17° are to be compared with the value α = 180 minutes, obtained by analysis of the residual, D(t). That this difference is caused essentially by the difference in definitions may be seen by subjecting the same observational data to different procedures of harmonic analysis. Specifically, the observations g(t) at Pasadena and Los Angeles have been harmonically analyzed by the following three different methods: (a) by the U. S. Coast and Geodetic Survey method [SCHUREMAN, 1941] with the assistance of the U. S. Coast and Geodetic Survey, (b) by the British Admiralty method [DOODSON and WARBURG, 1941]

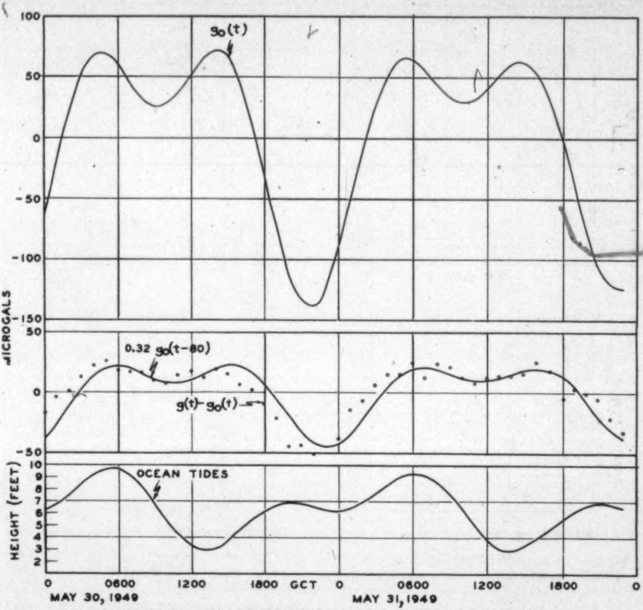

Fig. 4--Pasadena Station, May 30-31, 1949; standard error of points with respect to indicated comparison function = 7.7 microgals; drift = 0.095 microgal per hour

and (c) by a third method making direct use of the constants ϵ and α. This method is derived below.

In the classical method of harmonic analysis [DARWIN, 1908; SCHUREMAN, 1941] one writes

$$g(t) = \sum_i R_i \cos[(\omega_i t - \lambda_i) - K_i] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

and

$$g_o(t) = \sum_i R_{oi} \cos(\omega_i t - \lambda_i) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where ω_i are the so-called "speed numbers" and λ_i and K_i are the "epochs." Upon substituting this expression for $g_o(t)$ into (1) one obtains

$$g(t) = \sum_i R_{oi} \cos(\omega_i t - \lambda) + \epsilon \sum_i R_{oi} \cos[(\omega_i t - \lambda_i) - \omega_i \alpha] \quad \ldots\ldots\ldots\ldots \quad (4)$$

Solutions for K_i and R_i are now found by equating the right members of equations (2) and (4), namely

$$K_i = \tan^{-1}\left[\frac{\epsilon \sin \omega_i \alpha}{1 + \epsilon \cos \omega_i \alpha}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$R_i = R_{oi} \sqrt{1 + \epsilon^2 + 2\epsilon \cos \omega_o \alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

In Tables 2 and 3 are listed the values of R_i and K_i as computed by each of the above three methods. In the case of the USCGS and British Admiralty methods, the four smaller constituents P_1, N_2, K_2, and Q_2 have been inferred in the customary manner [SCHUREMAN, 1941, p. 78] from the values of the four major constituents M_2, K_1, O_1, and S_2. But in the case of the values deduced from

Table 2--Tidal amplitudes and phases for Los Angeles station computed by methods of U. S. Coast and Geodetic Survey, British Admiralty, and formula (1) (amplitudes in milligals)

ω	Harmonic constituent	R_i					R_{oi}	K_i				
		British Admiralty		USCGS		Formula (6)		British Admiralty		USCGS		Formula (5)
		Data A	Data B	Data A	Data B			Data A	Data B	Data A	Data B	
28.984	M_2	0.0699	0.0712	0.0690	0.0709	0.0639	0.0496	195.2°	194.7°	190.3°	190.8°	189.7°
15.041	K_1	0.0627	0.0675	0.0584	0.0613	0.0595	0.0449	210.2	179.2	179.5	179.5	185.2
13.943	O_1	0.0400	0.0416	0.0395	0.0392	0.0451	0.0339	188.8	190.3	184.8	182.2	184.8
30.00	S_2	0.0335	0.0345	0.0329	0.0337	0.0305	0.0239	188.8	[illegible]	192.4	187.9	190.0
14.959	P_1	0.0208	0.0223	0.0193	0.0203	0.0179	0.0135	210.2	179.2	179.5	179.5	185.1
28.440	N_2	0.0142	0.0144	0.0151	0.0149	0.0123	0.0096	139.3	193.5	179.8	185.6	189.5
30.082	K_2	0.0091	0.0094	0.0089	0.0092	0.0108	0.0084	188.8	184.4	192.4	187.9	190.0
13.399	Q_1	0.0078	0.0081	0.0087	0.0076	0.0088	0.0066	178.1	195.9	187.5	183.6	184.6

Data A is for the 29-day period with middle date August 3, 1949.
Data B is for the 29-day period with middle date August 15, 1949.

(5) and (6) all eight constituents have been determined directly from these formulas. Table 4 lists the values of Love's number for each harmonic constituent, computed by British Admiralty, USCGS, and (6). In Table 5 are shown (a) the ratios of the amplitudes computed by the USCGS method to those computed by the British Admiralty method, and (b) the corresponding ratios of values computed by the USCGS method to those computed by (6).

It will be noted that the corresponding phase values as computed by the several methods frequently differ among themselves by as much as five degrees; furthermore, in the 27 values listed for the four major components, only four depart from 180° by more than 11°. (The value

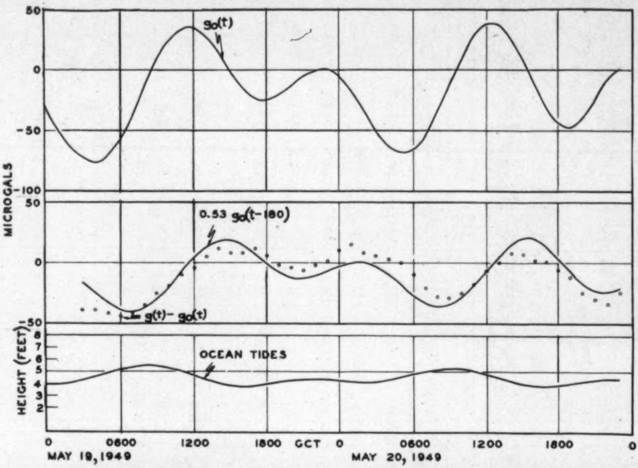

Fig. 5--Honolulu, Hawaii, May 19-20, 1949; standard error of points with respect to indicated comparison function = 9.6 microgals; drift = -1.5676 microgals per hour

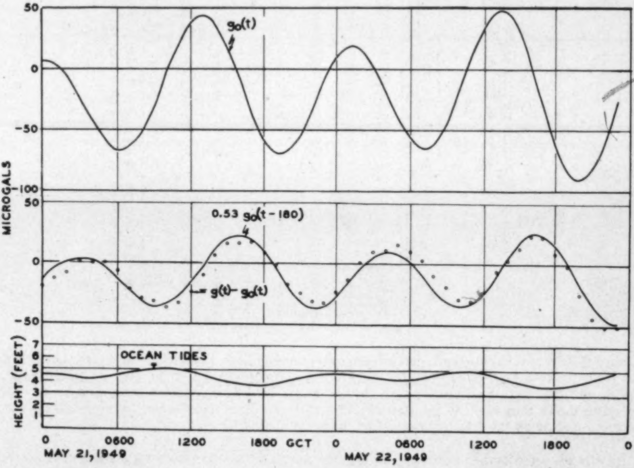

Fig. 6--Honolulu, Hawaii, May 21-22, 1949; standard error of points with respect to indicated comparison function = 5.8 microgals; drift = 0.6890 microgal per hour

Table 3--Tidal amplitudes and phases for Pasadena station computed by methods of U. S. Coast and Geodetic Survey, British Admiralty, and formula (6) (amplitudes in milligals)

ω^0/hr	Harmonic constituent	British Admiralty	USCGS	Formula (6)	R_{oi}	British Admiralty	USCGS	Formula (5)	$\omega_1\alpha$
28.984	M_2	0.0628	0.0650	0.0617	0.0495	192°.1	187°.4	189°.1	38°.645
15.041	K_1	0.0548	0.0559	0.0576	0.0448	180.8	183.8	184.8	20.055
13.943	O_1	0.0351	0.0358	0.0434	0.0337	190.4	180.6	184.5	18.590
30.000	S_2	0.0317	0.0310	0.0295	0.0238	186.8	185.1	189.4	40.000
14.959	P_1	0.0181	0.0185	0.0172	0.0134	180.8	183.8	184.8	19.940
28.440	N_2	0.0122	0.0129	0.0119	0.0096	206.5	193.1	188.7	37.911
30.082	K_2	0.0086	0.0084	0.0105	0.0084	186.8	185.1	189.4	40.108
13.399	Q_1	0.0068	0.0069	0.0085	0.0066	195.2	179.0	184.3	17.865

Data is for 29-day period with middle date May 31, 1949

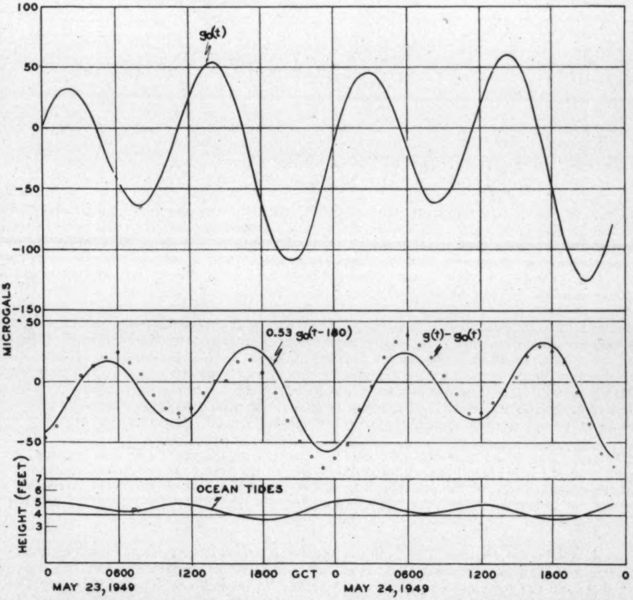

Fig. 7--Honolulu, Hawaii, May 23-24, 1949; standard error of points with respect to indicated comparison function = 10.0 microgals; drift = -0.4495 microgal per hour

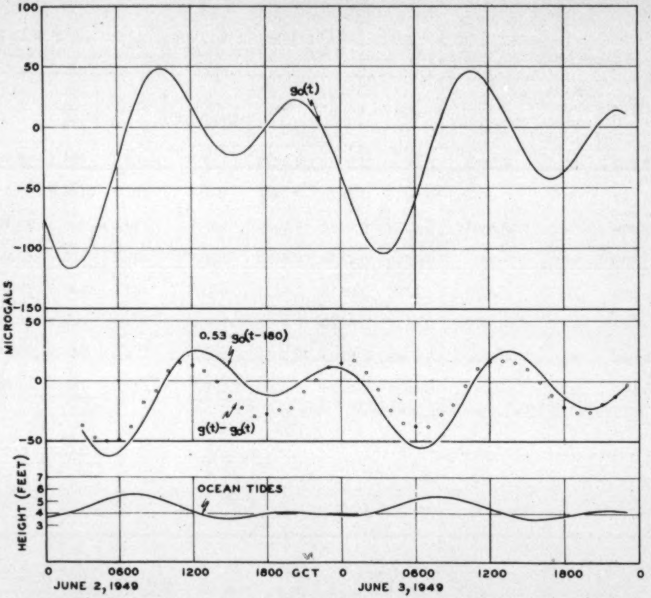

Fig. 8--Honolulu, Hawaii, June 2-3, 1949; standard error of points with respect to indicated comparison function = 11.6 microgals; drift = 0.3468 microgal per hour

of 210° 02′ by the British Admiralty method for K_1, data A, is exceptional, and possibly an error. It has been disregarded.) None of the 16 phase values computed from (5) departs from 180° by more than ten degrees. The significance of such small differences tends to be obscured in the random fluctuations in the data listed. These small values then appear to be less significant than is in reality the case, for they all were derived from data which yield a well-established phase lag in the residual function of 20° ± 5°.

In respect to the amplitudes, the results furnished by the three methods of analyzing the same data are in good accord. The discrepancies are generally less than five microgals; percentagewise, they are of the order of ten percent or less. Each of the methods appears to be satisfactory in the sense that the differences between their respective results are of a magnitude consistent with the experimental errors of the observations. It is our experience that the adopted process of harmonic analysis itself introduces minor discrepancies, partly because the periodicities involved are incommensurable.

The quantities ϵ and α as defined above are constant at Pasadena and Los Angeles, within the precision of the present observational data. When this is true, the proposed method of representing the observations by the residual function $\epsilon g_o(t-\alpha)$, and of obtaining the harmonic constituents from equations (5) and (6), is much more convenient than the classical methods of harmonic analysis.

Conclusions--The residual D(t) in the vertical component of gravity has been evaluated at four stations in three widely separated areas. Of these, the observations at Los Angeles, Pasadena and Hawaii are the most extensive and reliable. At these three stations D(t) may be reasonably well approximated by (1), with α and ϵ nearly constant in time at a given station. The

Table 4--Love's number $(1 + h - 3k/2) = R_i/R_{oi}$

Harmonic constituent	Los Angeles					Pasadena		
	British Admiralty		USCGS		Formula (6)	British Admiralty	USCGS	Formula (6)
	Data A	Data B	Data A	Data B				
M_2	1.409	1.435	1.391	1.429	1.288	1.269	1.313	1.246
K_1	1.396	1.503	1.301	1.365	1.325	1.223	1.248	1.286
O_1	1.180	1.227	1.165	1.156	1.330	1.042	1.062	1.288
S_2	1.397	1.444	1.377	1.410	1.276	1.332	1.303	1.239
P_1	1.541	1.652	1.430	1.504	1.325	1.351	1.381	1.284
N_2	1.479	1.500	1.573	1.552	1.281	1.115	1.344	1.240
K_2	1.083	1.119	1.060	1.095	1.285	1.024	1.000	1.250
Q_1	1.182	1.227	1.167	1.152	1.333	1.030	1.045	1.288

Table 5--Comparison of amplitudes as computed by methods of U. S. Coast and Geodetic Survey, British Admiralty, and formula (6)

Constituent	Ratio of the amplitudes computed by USCGS method to the amplitudes computed by British method			Ratio of the amplitudes computed by USCGS method to the amplitudes computed by formula (6)		
	Los Angeles		Pasadena	Los Angeles		Pasadena
	Period A	Period B		Period A	Period B	
M_2	0.987	0.995	1.035	1.079	1.109	1.053
K_1	0.931	0.908	1.020	0.981	1.030	0.970
O_1	0.987	0.942	1.019	0.875	0.869	0.824
S_2	0.982	0.971	0.977	1.078	1.104	1.050
P_1	0.927	0.910	1.022	1.078	1.134	1.075
N_2	1.063	1.034	1.057	1.227	1.211	1.084
K_2	0.978	0.978	0.976	0.824	0.851	0.800
Q_1	0.987	0.938	1.014	0.875	0.863	0.811

phase shift α is large; furthermore, the difference between the phase at the California stations and the two other stations is also large, about five times the estimated standard error of the phase determinations. There are indications that the amplitude factor ϵ also changes with geographic position, but no unequivocal conclusion concerning this point is obtained from the present data.

From knowledge of the phase and amplitude parameters, when these are constant, the classical harmonic tidal constituents are easily computed. Comparison is made in the case of the Pasadena and Los Angeles data between the results of this method of computing the tidal constituents and the classical procedure exemplified by the USCGS method and the British Admiralty method. The discrepancies among the resultant values are small, of magnitude consistent with the known degree of uncertainty in the primary observational data.

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INDUCTION BY A HORIZONTAL OSCILLATING MAGNETIC DIPOLE OVER A CONDUCTING HOMOGENEOUS EARTH

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Abstract--The magnetic field of an oscillating horizontal magnetic dipole on the surface of a homogeneous Earth is calculated. For lower frequencies, where displacement currents can be neglected, the magnetic field on the surface of the Earth can be represented in terms of transcendental and cylindrical functions. Particular attention is paid to the vertical component, which vanishes as the conductivity of the Earth approaches zero. An explicit formula is given for the value of this component in parametric form involving the conductivity, frequency, and distance to the observer. The magnetic field components tangential to the Earth's surface are also considered.

Introduction--The magnetic field resulting from current-carrying wires over a conducting Earth has been the subject of investigations on several occasions. The formal solutions of both vertical and horizontal magnetic dipoles over a conducting Earth have been given by Sommerfeld. Extensions of Sommerfeld's results have been made frequently in the study of radio propagation. Less attention, however, has been paid to any analysis of the field at relatively lower frequencies and at points near the dipole. FOSTER [1931] has considered the mutual impedance of grounded, insulated wires on a conducting half-space. Extensions of this work have been carried out by STEFANESCU [1942] who applies the results to geophysical prospecting. PRICE [1950] has studied the induction from an infinite current wire situated over a conducting half-space. GORDON [1951ab] has given solutions for the magnetic field of an oscillating vertical magnetic dipole on the surface of a conducting half-space. The author [WAIT, 1951] has investigated the vertical magnetic dipole over a stratified medium.

The horizontal magnetic dipole over the flat semi-infinite conducting homogeneous Earth will be considered here. Explicit expressions will be calculated for the magnetic field components on the surface of the Earth. M.K.S. rationalized units will be adopted throughout.

The magnetic dipole of strength C, which varies harmonically with time as exp $(i\omega t)$, is situated at the origin and oriented in the y direction of a cartesian coordinate system. The physical counterpart of this magnetic dipole is a small circular loop of area dA carrying a total circulating current I and whose axis is oriented in the y direction. For any of the following formulas C can be replaced by $i\mu\omega IdA/4\pi$ where μ is the magnetic permeability of the surrounding space. The Earth's surface coincides with the xy-plane. The dielectric constant, permeability, and conductivity of the homogeneous Earth material are designated by ϵ_1, μ_1, and σ_1, respectively. The air has a dielectric constant and permeability ϵ_o and μ_o respectively.

The field components for this problem can be expressed in terms of a magnetic Hertz vector F as defined by SCHELKUNOFF [1943, p. 128] which has components in the z and the y directions only. SOMMERFELD [1926] has shown that the x-component is zero for this case. The electric and magnetic fields are given everywhere by

$$\begin{aligned} E &= -\,\mathrm{curl}\,F \\ i\mu\omega H &= -\gamma^2 F + \mathrm{grad\ div}\,F \end{aligned} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where $\gamma^2 = i\sigma\mu\omega - \epsilon\mu\omega^2$. A subscript 0 or 1 is added to the quantities to indicate that they pertain to the air medium or the Earth medium.

Following the procedure outlined by SOMMERFELD [1926] the components of F for the air medium are given as follows for the case $\mu_1 = \mu_o$

$$\left.\begin{aligned} F_{ox} &= 0 \\ F_{oy} &= 2C \int_0^\infty [\gamma_1^2/(u_o \gamma_1^2 + u_1 \gamma_o^2)]\, e^{-u_o z}\, \lambda\, J_o(\lambda\rho)\, d\lambda \\ F_{oz} &= 2C \frac{\partial}{\partial y} \int_0^\infty \frac{(\gamma_1^2 - \gamma_o^2)\, e^{-u_o z}\, \lambda}{(u_1 + u_o)(u_o \gamma_1^2 + u_1 \gamma_o^2)}\, J_o(\lambda\rho)\, d\lambda \end{aligned}\right\} \qquad (2)$$

where $u_1 = (\lambda^2 + \gamma_1^2)^{1/2}$, $u_o = (\lambda^2 + \gamma_o^2)^{1/2}$, and $\rho^2 = x^2 + y^2$. The divergence of F_o is then given by

$$\text{div } F_o = 2C \frac{\partial}{\partial y} \int_0^\infty \frac{(\gamma_1^2 u_1 + u_o \gamma_o^2)\, e^{-u_o z}\, \lambda}{(\gamma_1^2 u_o + u_1 \gamma_1^2)(u_1 + u_o)}\, J_o(\lambda\rho)\, d\lambda \qquad (3)$$

This formal expression has no approximations. It will now be desirable to consider the case when displacement currents in the air are neglected. This is equivalent to stating that the fields in the air are a solution of Laplace's equation, or that significant dimensions in the physical situation are always much less than the free-space wavelength.

The divergence of F_o is then the magnetic potential Φ in the air where γ_o is set equal to zero and the subscript 1 is dropped

$$\Phi = -\text{div } F_o = -2C \frac{\partial}{\partial y} \int_0^\infty u(\lambda + u)^{-1} e^{-\lambda z} J_o(\lambda\rho)\, d\lambda \qquad (4)$$

where $u = (\lambda^2 + \gamma^2)^{1/2}$ and $\gamma = \gamma_1$.

Vertical magnetic field--An explicit expression will now be calculated for the vertical component H_z of the oscillating magnetic field on the surface of the Earth.

$$i\mu\omega H_z = 2C \frac{\partial^2}{\partial y \partial z} \int_0^\infty e^{-\lambda z}\, u(\lambda + u)^{-1} J_o(\lambda\rho)\, d\lambda \qquad (5)$$

and at z = 0 this can be written

$$i\mu\omega H_z = -C \frac{\partial}{\partial y} \int_0^\infty (u - \lambda)(u + \lambda)^{-1} \lambda J_o(\lambda\rho)\, d\lambda \qquad (6)$$

using $\int_0^\infty \lambda J_o(\lambda\rho)\, d\lambda = 0$ which is a special case of a formula given by WATSON, [1944, p. 386, no. 6] with $a = \nu = 0$. This can be written as follows employing a formula given by WATSON [1944, p. 386, no. 7] for the representation of $(u - \lambda)(u + \lambda)^{-1}$ as an integral

$$i\mu\omega H_z = -2C \frac{\partial}{\partial y} \int_0^\infty \int_0^\infty e^{-\lambda t} J_2(\gamma t)\, t^{-1}\, dt\, \lambda J_o(\lambda\rho)\, d\lambda \qquad (7)$$

The integration with respect to λ of the above equation can be carried out by employing the Lipschitz integral given by Watson, page 384.

$$\int_0^\infty e^{-a\lambda} J_o(b\lambda)\, d\lambda = (a^2 + b^2)^{-1/2} \qquad (8)$$

with the real part of a greater than zero. This integral is now differentiated under the integral sign with respect to a to give

$$\int_0^\infty \lambda e^{-a\lambda} J_o(\lambda b)\, d\lambda = a(a^2 + b^2)^{-3/2} \qquad (9)$$

Using this result the expression for H_z is written in the form

$$i\mu\omega H_z = 2C \frac{\partial}{\partial y} \frac{1}{\rho} \frac{\partial}{\partial \rho} \int_0^\infty \frac{J_2(\gamma t)\, dt}{(t^2 + \rho^2)^{1/2}} \qquad (10)$$

The infinite integral in the above expression is now a special case of a formula given by WATSON [1944, p. 435, no. 3] with $\nu = 2$.

Then

$$i \mu \omega H_z = \frac{2Cy}{\rho} \frac{\partial}{\partial \rho} \frac{1}{\rho} \frac{\partial}{\partial \rho} [I_1 (\gamma \rho /2) K_1 (\gamma \rho /2)] \quad \ldots\ldots\ldots\ldots (11)$$

The differentiations can be carried out using the well-known recurrence relations between Bessel functions given by WATSON [1944, p. 79], to yield

$$i \mu \omega H_z = \frac{Cy}{\rho 4} [\gamma^2 \rho^2 (I_1 K_1 - I_o K_o) + 4 \gamma \rho \ (I_1 K_o - I_o K_1) + 16 I_1 K_1] \quad \ldots (12)$$

where the argument of the Bessel functions is $\gamma \rho/2$ throughout. The field can be written in terms of real and imaginary parts designated by P and Q respectively, which are functions of the frequency f (= $\omega/2\pi$), the conductivity and the horizontal separation ρ between the horizontal magnetic dipole and the point of observation.

$$i \mu \omega H_z = - C y \rho^{-4} (P + i Q) \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

The functions P and Q have been calculated over a range of values of $|\gamma \rho|$. The results of the computations are shown in Table 1.

Table 1--Values of P and Q

$\|\gamma \rho\|$	P	Q
0	0.000	0.000
0.2	0.000	0.010
0.4	0.003	0.039
0.8	0.030	0.142
1.2	0.101	0.300
1.6	0.228	0.413
2.0	0.394	0.480
3.0	0.877	0.523
6.0	1.183	0.390
9.0	0.533	0.481
12.0	0.367	0.330
15.0	0.295	0.270

At much higher frequencies the calculated values would not be significant since displacement currents in the air would become appreciable. (A review has pointed out that the expression for the vertical field component in (12) is almost identical in form with the expression derived by GORDON [1951a] for the horizontal magnetic field component of a vertical magnetic dipole. In fact, by proper use of the reciprocity theorem (12) can be obtained directly from Gordon's results.)

Horizontal magnetic fields--The components of the tangential magnetic fields above the Earth and at its surface can be written

$$i \mu \omega H_x = - \frac{\partial \Phi}{\partial x} \text{ and } i \mu \omega H_y = - \frac{\partial \Phi}{\partial y} \quad \ldots\ldots\ldots (14)$$

where Φ has been defined by (4). The function Φ will now be evaluated on the surface of the Earth at z = 0 and designated as Φ_o and given by

$$\Phi = \frac{2Cy}{\rho} \int_0^\infty \lambda \, u \, (\lambda + u)^{-1} J_1 (\lambda \rho) \, d\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

This can be rewritten in the form

$$\Phi_o = \frac{2Cy}{\gamma^2 \rho} \int_0^\infty \lambda \, u \, (u - \lambda) \, J_1 (\lambda \rho) \, d\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

where the identity $u^2 - \lambda^2 = \gamma^2$ is made use of. This can be broken up into the following three integrals

$$\Phi_o = \frac{2Cy}{\gamma^2 \rho} \left[\int_0^\infty \lambda^3 J_1 (\lambda \rho) \, d\lambda + \gamma^2 \int_0^\infty \lambda \, J_1 (\lambda \rho) \, d\lambda - \int_0^\infty \lambda^2 \, u \, J_1 (\lambda \rho) \, d\lambda \right] \quad \ldots (17)$$

The first and second integrals can be found from the Lipschitz integral

$$\int_0^\infty e^{-\lambda z} \, J_o (\lambda \rho) \, d\lambda = (\rho^2 + z^2)^{-1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

This integral is differentiated once with respect to ρ, then twice with respect to z, and then setting z = 0 the first integral in (17) is obtained. The second integral is obtained by only a single differentiation with respect to ρ, again setting z = 0.

The third integral in equation is obtained from SOMMERFELD's [1926] integral.

$$\int_0^\infty \lambda \, e^{-uz} \, u^{-1} \, J_o (\lambda \rho) \, d\lambda = \frac{e^{-\gamma r}}{r} \quad \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

where $r = (\rho^2 + z^2)^{1/2}$ and is valid for $z \geq 0$.

This integral is differentiated once with respect to ρ then twice with respect to z before setting z = 0.

The complete expression for Φ_o is then written symbolically as follows

$$\Phi_o = \frac{2Cy}{\gamma^2 \rho}\left[\frac{\partial^3}{\partial\rho\partial z^2}\,\frac{e^{-\gamma r}-1}{r} - \gamma^2 \frac{\partial}{\partial\rho}\frac{1}{r}\right]_{z=0} \qquad \ldots\ldots\ldots\ldots\ldots (20)$$

These operations can be carried out to yield

$$\Phi_o = \frac{2Cy}{\gamma^2 \rho^5}\left[(3 + 3\,\gamma\rho + \gamma^2\rho^2)\,e^{-\gamma\rho} - 3 + \gamma^2\rho^2\right] \qquad \ldots\ldots\ldots\ldots (21)$$

At small values of the parameter $|\gamma\rho|$, the magnetic potential approaches the value Cy/ρ^3, whereas at very large values of the parameter the potential approaches the value $2Cy/\rho^3$. This is in accord with the usual theory of images at the boundary between a highly conducting medium and an insulator.

The H_x and H_y components of the magnetic field on the surface of the Earth can be found by differentiation of Φ_o with respect to x and y respectively.

$$\left.\begin{aligned} i\,\mu\,\omega\,H_x &= -\,CN\,x\,y\,\rho^{-3} + C\frac{\partial N}{\partial\rho}x\,y\,\rho^{-2} \\ i\,\mu\,\omega\,H_y &= CN\,x^2\,\rho^{-3} + C\frac{\partial N}{\partial\rho}y^2\rho^{-2} \end{aligned}\right\} \qquad \ldots\ldots\ldots\ldots\ldots (22)$$

where

$$N = -2\gamma^{-2}\rho^{-4}\left[(\gamma^2\rho^2 + 3\,\gamma\rho + 3)\,e^{-\gamma\rho} + \gamma^2\rho^2 - 3\right]$$

$$\frac{\partial N}{\partial\rho} = 2\,\gamma^{-2}\,\gamma^{-5}\left[(\gamma^3\rho^3 + 5\,\gamma^2\rho^2 + 12\,\gamma\rho + 12)\,e^{-\gamma\rho} - 12 + 2\,\gamma^2\rho^2\right]$$

These tangential field expressions could also be obtained from the results of BELLUIGI [1949] who formulated the problem of a single magnetic pole over a flat conductive semi-infinite region. He gave no results, however, for the vertical component of the magnetic field.

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A RELATION BETWEEN FREQUENCIES OF CLOUD COVER AND CLOUD HEIGHT

George L. Arnold

Abstract--A method of relating the frequency of six tenths or more sky cover to the frequency of various ceiling heights is presented to show how the latter may be estimated in areas where only total sky cover has been observed and recorded. Tests show that the method has significant value above 1000 ft.

Introduction--A method to estimate the frequency of ceiling heights (six tenths or more clouds) in areas where only cloud cover data are available is often desired. It is important in many phases of planning, especially those connected with aircraft operations, to have such a working tool. This investigation was limited to stations where standard climatic summaries of ceiling frequencies were available. The problems of interpolating between standard levels and of estimating frequencies of ceilings above the highest cloud heights normally reported, 9750 ft, were included in this investigation. All procedures were carried out using graphical solutions insofar as possible. The purpose of this paper is to outline the procedure, results, and conclusions drawn from this investigation.

Observational material--Data used were taken from U. S. Air Force Form 94B summaries for 68 stations in eastern United States. Mean values obtained from combining summarized hourly data for December, January, and February were used, giving the percentage frequency of ceilings occuring at or below five standard levels, 950, 2050, 3050, 5250, and 9750 ft. At least six tenths cloudiness is necessary to constitute a ceiling in this summarization. The frequency of six tenths

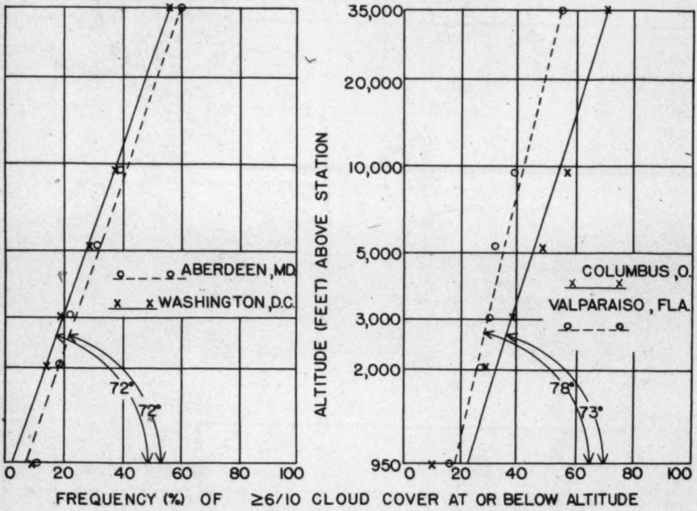

Fig. 1--Computation of index numbers using average values of hourly ceiling heights for Dec., Jan., and Feb.

or more sky cover for the same observations were also used. The lengths of these records range from four to 14 years. Twenty-four stations used in the development phase had nine to 14 years of records, except three stations with five to six years of records. Forty-four stations used in testing the technique had records ranging from four to eight years. Over a million observations are included in the summaries from these 68 stations.

Relation of ceiling frequency and altitude--The initial phase of this investigation resulted in development of a simple equation reasonably common to stations in eastern United States

$$\log z = a + bf$$

where z is the altitude in feet above the station, a and b are constants, and f is the frequency of ceilings at or below altitude z. The equation is applied below 35,000 ft, and it is assumed that there is no further increase in frequency above this altitude. A preliminary investigation showed that the frequency became insensitive with respect to altitude changes around this level during winter. The constant, a, generally reflects local effects as well as unevenly distributed large-scale effects, while b appeared to be a geographically distributed large-scale effect. This will become more evident as the method is developed. Instead of solving the equation for each station mathematically, a graphical solution was used as shown in Figure 1.

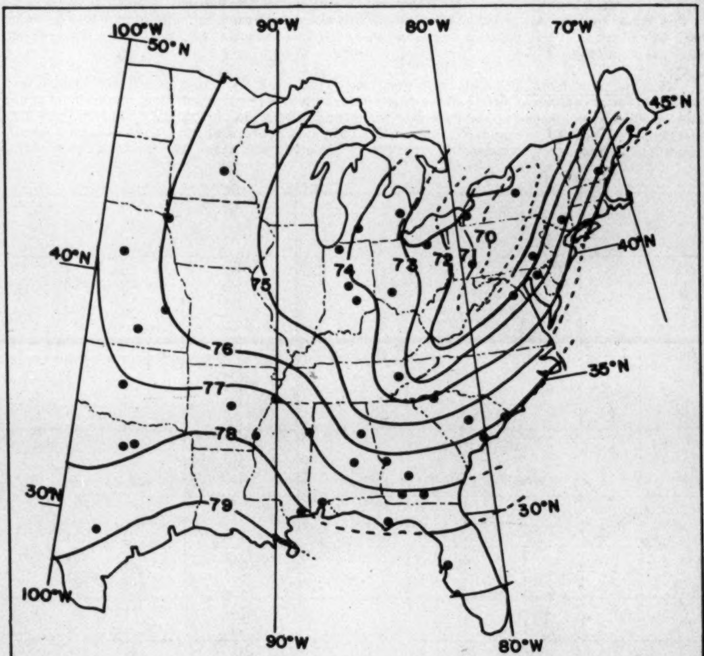

Fig. 2--Geographical distribution of index numbers; dashed lines indicate index uncertain or not investigated; dots show location of the stations used in test technique

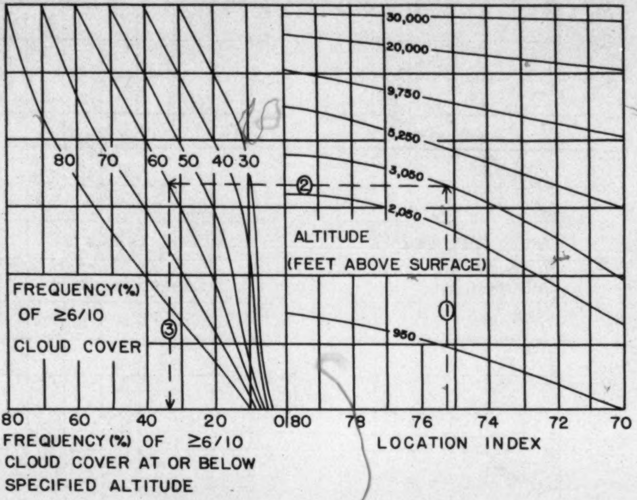

Fig. 3--Climagraph of ceiling height frequencies

The points used in the analysis of Figure 1 were taken from the climatic summaries giving percentage frequency of ceilings at or below the standard levels. For each level, the frequency in per cent was plotted against the altitude above station (on the log scale). The percentage frequency of six tenths or more sky cover at the station was plotted at 35,000 ft. A straight line was then fitted by eye from the top point in a manner so as to keep the errors of fit less than five per cent at the 9750-, 5250-, and 3050-foot levels and yet draw as close as possible to the 2050- and 950-foot levels. This line, however, did not always fit well at the two lowest levels. Stations in the southwest desert areas and some stations west of the Rocky Mountains presented some problems in analysis that will require additional investigation.

Two significant factors were noted in this analysis of individual stations. First, the slopes of the fitted lines for two stations located close together were similar even though the percentage frequency value at similar altitudes for one was greater than the other. For example, the slopes at Washington, D. C., and Aberdeen, Maryland, are similar; the slopes at these stations, however, differ from that at Valparaiso, Florida. There seemed to be a definite geographical influence on the slopes of these lines, which had a sufficiently gradual and uniform gradient from one portion of the country to another to warrant further investigation. The slopes of the individual stations used in the development were plotted and analyzed as shown in Figure 2. The points show the stations used in the test of the technique, and were not used in the drawing of the isopleths. No lines were drawn to deviate over one index number plus or minus from any plotted index value. This index map is the means of expressing the geographical variation of the index. The second significant factor noted was that the deviation at low ceiling heights from the straight-line analysis, Figure 1, was influenced by both the slope of the line and the percentage frequency of six tenths or more cloud cover. In an attempt to express quantitatively the influence of these two factors, a graphical correlation (coaxial method) described in detail by LINSLEY, KOHLER, and PAULHUS [1949] was used as a convenient method of relating the four parameters shown in the climagraph, Figure 3. Figures 2 and 3 form the working tools for estimating the per cent frequency of ceilings at or below any altitude when the location of the station and the per cent frequency of six tenths or more sky cover is known.

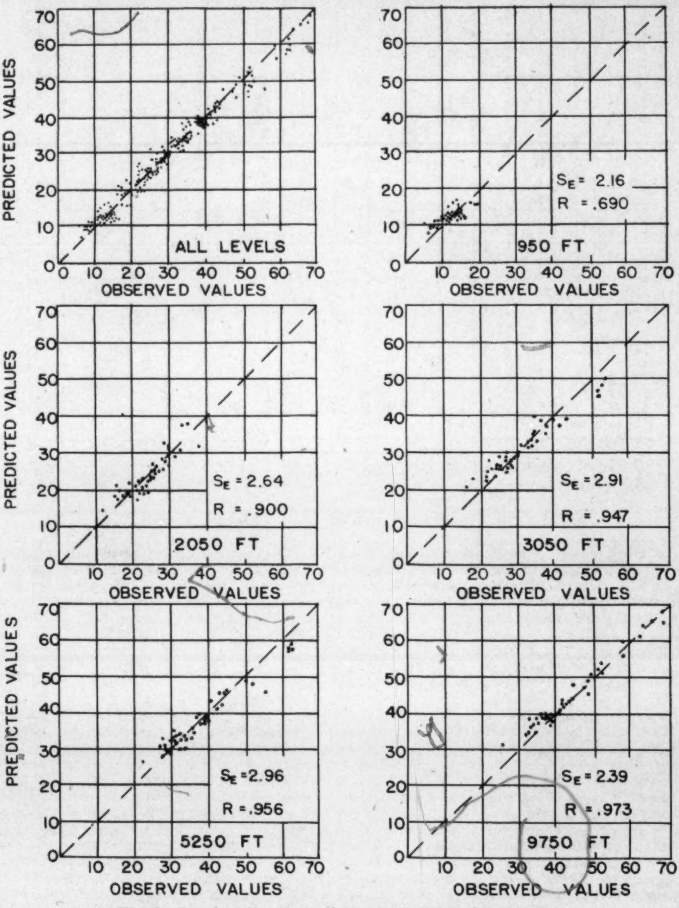

Fig. 4--Results of testing technique with fourty-four stations shown in Figure 2 and not used in development

Test of climagraph--To test the graphically derived relations, 44 stations, not used in developing the relations, were used in estimating percentage frequency of six tenths or more cloudiness below the standard levels. This provided 220 points to process through the climagraph. Only the frequency of six tenths or more cloud cover and the location, Figure 2, of the stations were used to estimate these frequencies. The periods of record (four to eight years) were shorter than those used in the development. Figure 4 shows the results of comparing 220 estimated percentages with the actual percentages. These figures show the amount of scatter about the line of perfect correlation. The scatter diagram, including all levels, presents the verification for the overall relationship of the technique. The multiple correlation coefficients are presented on the scatter diagrams for each standard level along with its standard error of estimate. Apparently there are factors below 2000 ft that are not taken into account by this technique as shown by the sharp drop in $R = 0.900$ at 2050 ft to $R = 0.690$ at 950 ft.

The standard error of estimate and multiple correlation coefficients (Fig. 4) are probably representative of levels between the standard levels. The standard error of estimate and multiple correlation coefficients that might be expected in testing this relationship above 9750 ft are not clear-cut. Cloud data observed since early 1949 include ceilings well above 9750 ft. Two years of these data for December, January, and February were summarized for five stations scattered throughout the eastern United States, representing about 4,300 observations per station. These data were summarized in the same manner as used in the development for frequency of ceilings at or below 400, 900, 2000, 3000, 5200, 9700, 15000, 30000 and above 30000 ft, but the records are too short to draw definite conclusions. The standard error of estimate of frequency above the 9750-foot level appears to be about the same magnitude as below 9750 ft, but by the very nature of the method the standard error of estimate approaches 0 at very high levels and R approaches 1.00 at very high altitudes when altitude becomes insensitive in the method.

Conclusions--It is felt that this technique of extending the use of cloud-cover data to provide estimates of ceiling-height frequencies is adequate for this specific climatological problem. In other similar climatological problems requiring the same type of extension of data but for different seasons, months, for specific times of day, or other than six tenths cloud-cover criteria, this general technique should provide a worth-while direction of investigation.

Acknowledgments--The writer wishes to express his appreciation to the Directorate of Climatology, Air Weather Service, Andrews Air Force Base, Washington, D. C., for providing the climatological data used in this paper, and to George P. Wadsworth, Department of Mathematics, at Massachusetts Institute of Technology, for his comments concerning the correlation coefficients.

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WIND EFFECT ON RINGKÖBING FJORD

B. Hellström

Abstract--An investigation into the effect of the wind on the elevation of the water level of Ringköbing Fjord, Denmark, has provided a check on the general theory of the wind effect on lakes previously published by the author.

Ringköbing Fjord--On the west coast of Denmark there is an inland lake, Ringköbing Fjord, which, owing to its size and small depth, is subject to fairly great variations in the water level, due to the effect of wind. A map of the lake is shown in Figure 1. In round figures, the lake is 28 km long (north to south), 11 km wide, and has an area of 294 km^2. The catchment area is 3000 km^2. The average depth is about 1.7 m and the maximum depth five meters. The bottom contours are shown in Figure 1. The lake is separated from the North Sea by a long, narrow strip of land, Holmsland Klit, one to two kilometers in width. The natural outlet from the lake to the North Sea lies at the south end of the lake at Nymindegab, but an artificial outlet has been created at Hvidesande in the middle of Holmsland Klit. At Hvidesande there is a barrage, containing 14 gates for discharge of water to the North Sea, and a lock, 34 m long and 8.5 m wide. At the lock there is a harbor for fishing vessels. When the works were completed in 1931 the natural outlet at Nymindegab was closed. The gates in the barrage are designed so that the North Sea is prevented from discharging water into the lake at storm flood in the North Sea, and the water level is normally kept between 0.0 m and 0.4 m above mean sea level in the North Sea.

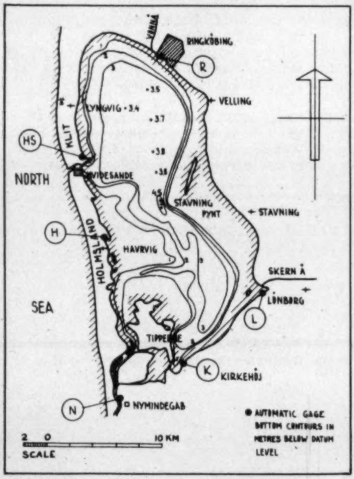


Fig. 1--Map of Ringköbing Fjord

The variation of the water level has been registered since 1931 by six automatic gages located at Ringköbing (R), Lönborg (L), Kirkehöj (K), Nymindegab (N), Havrvig (H) and Hvidesande (HS) shown in Figure 1.

The velocity and direction of the wind are measured about five meters above ground level at Hvidesande and about two meters at Lyngvig, the latter being situated on Holmsland Klit, north of Hvidesande. These data can also be obtained from the weather charts. The wind velocity is expressed in Beaufort.

General theory--A general study of the effect of the wind on the variation of the water level in lakes has previously been published [HELLSTRÖM, 1941ab], and the theories advanced were found to agree closely with observations made during storms on many lakes in the United States, Sweden and elsewhere.

The differential equation for the gradient of the water surface is

$$dz_o/dx = \kappa k/\gamma (z_o - z_1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where z_o = the coordinate of the water surface; z_1 = the coordinate of the bottom; $(z_o - z_1)$ = depth of water; k = wind force or tangential stress on the water surface; γ = volume weight of water; and κ = a constant, 1.5.

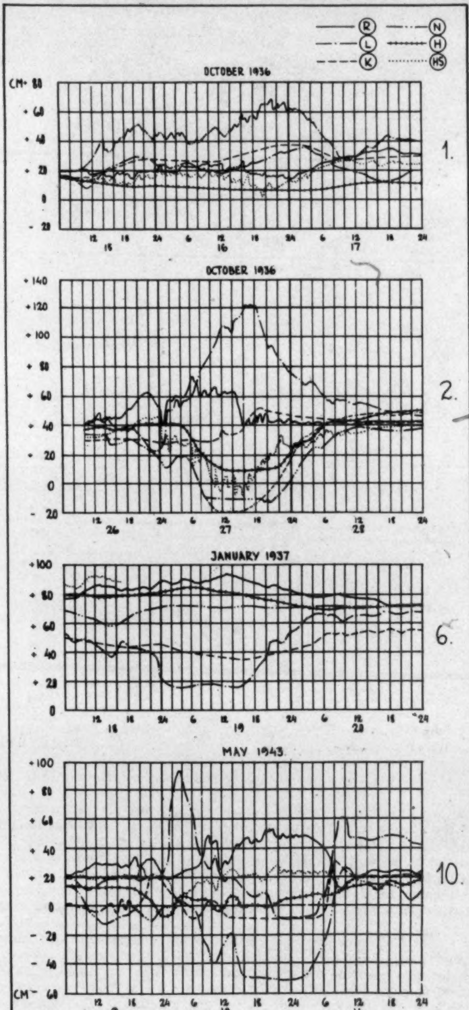


Fig. 2--Hydrographs for storms 1, 2, 6, and 10

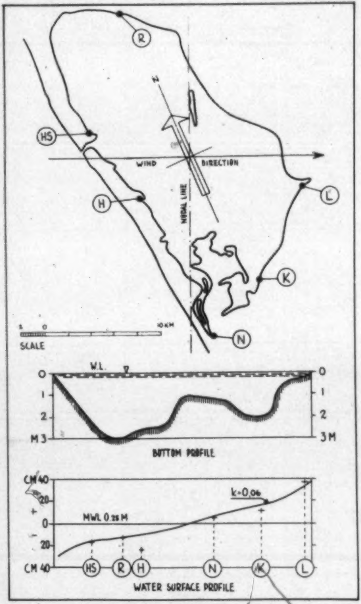


Fig. 3--Storm 1, wind direction WNW, wind velocity 17.5 m/sec

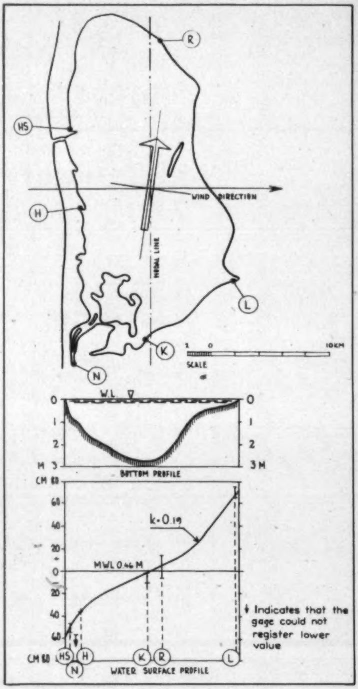


Fig. 4--Storm 2, wind direction W, wind velocity 29.2 m/sec

It should be noticed that the viscosity of the fluid does not enter into the equation.

The integration is most conveniently carried out graphically. As a first approximation it is assumed that the wind-affected water surface has the same elevation along any cross section of the lake, taken at right angles to the direction of the wind, and that the gradient at any point depends upon the average depth of the cross section of the lake, taken at right angles to the direction of the wind at that point. The problem then becomes two-dimensional as represented by (1). In certain cases local corrections have to be applied to the result so obtained. The integration constant is determined by the condition that the volume of water in the lake is constant.

Investigation 1951 of Ringköbing Fjord--In 1951 an investigation was made into the wind effect on Ringköbing Fjord [CARLSSON, and Others, 1951]. The investigation covered the conditions prevailing during 11 storms for the period 1936 to 1951 as listed in Table 1. During these occasions the maximum wind velocity varied between 8.6 and 29.2 m/sec and the maximum difference in elevation of the water level at any two gages reached, during the same storm, 1.40m.

The data relating to storms 1, 2, 6, and 10 are shown in Figures 2-6. In Figures 3-6 the map of the lake has been turned so that the wind blows either from left to right or from right to

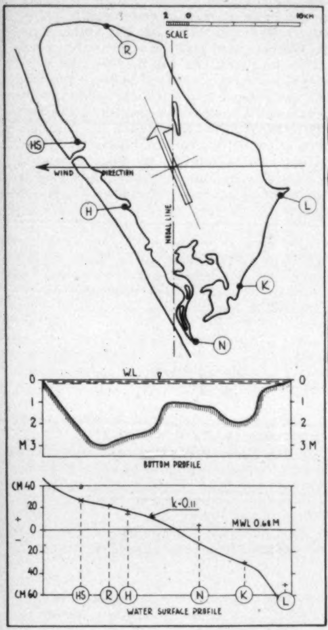
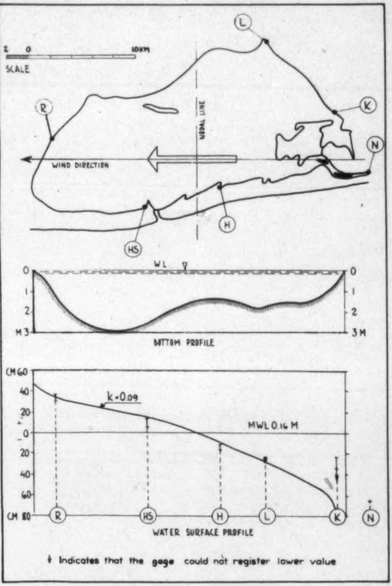


Fig. 5--Storm 6, wind direction ESE, wind velocity 23.3 m/sec



↓ Indicates that the gage could not register lower value

Fig. 6--Storm 10, wind direction S, wind velocity 18.6 m/sec

Table 1--Data on the storms studied

Storm	Date	Time	Wind direction	Wind velocity: Mean value Lyngvig and Hvidesande	Wind velocity: According weather chart	Wind velocity: Value chosen for computation	Wind force
		h h		m/sec	m/sec	m/sec	kg/m^2
1	Oct. 16, 1936	22-24	WNW	18.3	15.4	17.5	0.06
2	Oct. 26, 1936	14-16	W	30.0	28.4	29.2	0.19
3	Dec. 1, 1936	16-18	NW	20.0	23.0	21.6	0.10
4	Dec. 3, 1936	04-06	NW	14.0	10.3	13.0	0.04
5	Dec. 4, 1936	20-22	W	17.6	18.0	17.8	0.06
6	Jan. 19, 1937	08-10	ESE	23.5	23.2	23.3	0.11
7	Nov. 24, 1938	06-08	WSW	27.0	25.7	26.4	0.14
8	Mar. 28, 1939	06-08	ENE	15.2	15.4	15.3	0.055
9	May 9, 1943	11-13	S	9.8	7.7	8.8	0.03
10	May 10, 1943	20-22	S	19.2	18.0	18.6	0.09
11	July 3, 1951	18	WNW	8.0	10.3	8.6	0.019

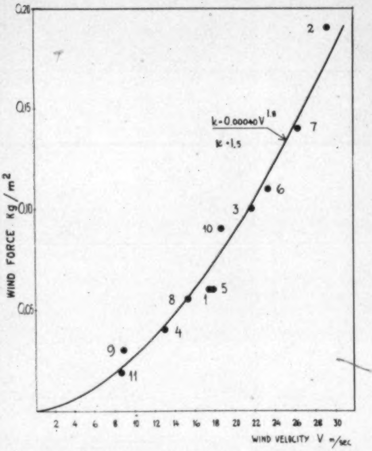


Fig. 7--Wind force related to wind velocity

left. The nodal line is shown in each. In each case, the solid curve which shows the water surface in the section has been computed as stated above, and the crosses and other symbols indicate the elevation of the water surface at the gages. As will be seen, there is generally a good agreement between the theoretically computed water surface and the observations. Owing to the position of the gage at Nymindegab the values from this point cannot be used for comparison between estimate and observation, but they have nevertheless been shown. In some instances, as shown (Fig. 4 and 6) the gage could not register lower value.

The value of the wind force for each storm is given in the diagrams and in Table 1. In Figure 7 these values are plotted against the wind velocities. As will be seen, they correspond well to the equation

$$k = 0.00040\ V^{1.8} \quad \ldots\ldots (2)$$

where V is the wind velocity in m/sec and k the wind force in kg/m².

The corresponding equation given in the general study [HELLSTRÖM, 1941a, p. 142], partly based on values from Lake Okeechobee, Florida, for wind velocities of up to 40 m/sec, has a value of the coefficient before V in (2) of 0.00037 instead of 0.00040 found for Ringköbing Fjord. The difference is insignificant, and the investigation accounted for in this paper is a good confirmation of the value of the wind force previously obtained. It is to be observed that the velocity of the wind at Ringköbing Fjord is given in the Beaufort scale, and that there is always the possibility of some inaccuracy in the conversion of Beaufort values into m/sec.

Acknowledgments--Acknowledgment is made of the valuable assistance during the investigation at the site rendered by L. M. Blok, District Engineer, Chr. Kusk-Christensen, Designing Engineer, and Mogens Jensen, Harbor Master.

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A NOTE ON THE REFLECTION OF DIFFUSE RADIATION BY THE SEA SURFACE

Wayne V. Burt

(Contribution No. 7 from the Chesapeake Bay Institute)

Abstract--Measurements of the reflection of diffuse solar radiation from the sea surface under a cloud cover are somewhat higher than Judd's theoretical value of 6.6 per cent for reflection of diffuse radiation by a flat water surface. Schmidt's usually accepted theoretical value of 17 per cent does not apply, and when his derivation is re-examined it leads to the same value as Judd's.

POWELL and CLARKE [1936] measured the albedo of the sea surface under a cloud cover with two photoelectric photometers. One was placed facing upward on deck, and the second was held in an inverted position over the water surface by a buoy. NEIBURGER [1948] measured the albedo of the sea surface under stratus clouds from a U. S. Navy blimp. He mounted one Eppley pyrheliometer above the blimp and a second pyrheliometer in an inverted position below the blimp. The writer measured the albedo of Chesapeake Bay waters from the research vessel Joanbar II, using two Eppley pyrheliometers. One instrument was mounted in an upright position at the masthead and a second was inverted over the water at the end of a 20-ft boom. Measurements were made during periods when the vessel rolled or pitched only a few degrees.

The results of the above observations are shown in Table 1.

Table 1--Summary of albedo measurements

Investigator	Number of observations	Mean albedo	Standard deviation
		pct	pct
Powell and Clarke	3 (series)	6.5	-
Neiburger	117	10.5	5
Burt	48	9.4	2

From theoretical considerations SCHMIDT [1915] computed an average albedo of 17 per cent for perfectly diffuse radiation striking a flat sea surface. Neiburger concludes that "the discrepancy from the theoretical (Schmidt's) value may be explained by the evidence showing that the radiation (passing through stratus clouds) is not completely diffuse."

It seems timely to re-examine Schmidt's method of calculation. His equation is

$$\text{per cent albedo} = \int_0^{\pi/2} r\,(h) \cos\,(h)\, dh \qquad \text{. . . . . (1)}$$

where r (h) is the reflectance according to Fresnel's formula for unpolarized light striking a plain water surface at an elevation angle of h [HARDY and PERRIN, 1932, p. 27]. It appears that Schmidt did not consider that any single beam of light energy with an intensity of I_o has a flux (energy per unit surface area) of I_o sin h. If this is taken into account, (1) becomes

$$\text{per cent albedo} = \int_0^{\pi/2} r\,(h) \sin 2\,(h)\, dh \qquad \text{. . . . . (2)}$$

Numerical integration of (2) yields an albedo of 6.6 percent, which agrees well with the average value found experimentally by Powell and Clarke and falls somewhat below the values found independently by Neiburger and the writer.

JUDD [1942] used a similar equation

$$\text{per cent albedo} = \sum_0^{\pi/2} r_\phi \sin 2\phi\Delta\phi \,/\, \sum_0^{\pi/2} \sin 2\phi\Delta\phi \qquad \text{. . . . . (3)}$$

(where $\phi = 90^\circ - h$) which was developed by McNICHOLAS [1928]. He employed values of r_ϕ published by MOON [1940] and arrived at an albedo of 6.6 per cent for perfectly diffuse radiation striking a plain water surface.

It therefore seems evident that those individuals working on heat and light energy budget studies should use a lower value for the sea surface albedo of diffuse radiation such as skylight or partially diffuse light passing through a cloud cover than that which has persistently appeared in the literature, for example, SVERDRUP, JOHNSON, and FLEMING [1946, p. 104].

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USE OF WATER BY NATIVE VEGETATION VERSUS GRASSES AND FORBS ON WATERSHEDS

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Abstract--Soil-moisture records from plots on potential range lands in California on which native vegetation, mostly woody brush species, was left intact, and from adjacent plots which were denuded by burning, were obtained for several years. Samplings, by which the amounts of soil moisture could be measured quantitatively, were taken with soil tubes generally under extremely difficult conditions at intervals frequently enough to give a satisfactory picture of the water regimen of the area. Over 23 paired plots were used in the experiments. They were selected to give a wide variety of vegetative types, rainfall patterns, topography, and soils. At all of the sites the rain generally fell from October through March; most of it was in December, January, and February. The growth of the plants, therefore, was dependent to a large extent upon the amount of water that could be stored in the soil mantle. Following the fire, grasses and forbs usually succeeded the brush, but, with some species, several annual burnings were necessary before it was eliminated. The removal of the brush resulted in saving of moisture. The soil was at a higher moisture content in the burned plots than in the unburned at the end of the growing season; consequently, less water was required to restore the soil in the burned plots to its field capacity. In most cases the results led to the conclusion that appreciable savings of water could be effected by burning to substitute grasses or forbs which have forage value. The soil-moisture records show that the soil in the burned areas was wet to its field capacity as early and, in many cases, earlier than in the unburned ones, thus indicating that the permeability of the soil for water was not adversely affected by burning.

The importance of clearing lands which have potential value for grazing livestock is increasing in the West. This is especially noted in California with its marked increase in population and need for meat and wool. There are vast areas in the State which are so densely covered with brush that grazing is impossible. The effect of removal of this vegetation and its substitution by grasses and forbs on the water regimen of the area has been the subject of study for a number of years by a group at the University of California. This report gives a summary of some of the results of the soil-moisture studies.

It has been pointed out [VEIHMEYER, 1927, 1938] that plant transpiration is the chief means by which water is lost from soils and that the loss of water by evaporation directly from the soil surface is almost entirely confined to a shallow surface layer. Water, when applied to dry soil, is rather quickly distributed until the field capacity is reached. After this, the movement of water, for practical purposes, may be considered to have ceased. The readily usable water in soil is the difference between the field capacity and the permanent wilting percentage. Surface evaporation will reduce the moisture below the permanent wilting percentage in a portion of the upper foot of soil; therefore, an additional amount must be allowed in estimating the storage capacity of the soil. The permanent wilting percentage is suggested as a reference for the measurement of soil moisture [VEIHMEYER and HENDRICKSON, 1948].

HENDRICKSON [1942] has discussed a method of determining losses of moisture from soils in a watershed area which has been followed in the investigations here reported. Some of the results of earlier studies have been reported [VEIHMEYER and JOHNSTON, 1944].

Clearing brush from watersheds offers a means of increasing water supplies. The success of the agricultural practice of summer fallowing, insofar as soil moisture is involved, depends upon carrying over the water stored in the soil from one season's rainfall to the next by keeping the land free of vegetation, thus eliminating the draught on the soil-moisture supply by plant transpiration.

Soil-moisture records from plots on potential range lands in California on which native vegetation, mostly woody brush species, was left intact, and from adjacent plots which were denuded by burning, were obtained for several years. Samplings by which the amounts of soil moisture could be measured quantitatively were taken with soil tubes, generally under extremely difficult conditions due to the stony and gravelly nature of some of the soils, at intervals frequent enough to give a satisfactory record of the water regimen of the area. A description of the plots is

Table 1--Plots used in determining soil moisture

Plot	Aver. rainfall[a] inch	Cover	Aver. slope	Soil
Button Canyon	43.55	Chamise	10.3	Primary, yellow or reddish clay grading into bedrock (Hugo)
Cold Fork	50.60	Chamise, manzanita	-	Primary, brownish clay loam with chocolate-brown clay subsoil (Hugo)
Ceanothus Gleason	51.68	Ceanothus	-	Primary, very rocky, not classified
Corning	72.26	Manzanita	-	Old valley-fill material (Corning)
Diamond Range	49.85	Manzanita, oak, pine	30.9	Old valley-fill material (Corning)
Holland	68.30	Manzanita, oak, pine	18.1	Primary, granitic (Holland)
Inskip	51.42	Manzanita, some oak	-	Primary, volcanic, not classified
Lake	30.17	Scrub oak	38.7	Primary, volcanic, not classified
Madera no. 1	11.35	Oak, ceanothus	18.3	Primary, granitic (Holland)
Madera no. 2	11.12	Oak, ceanothus	15.9	Primary, granitic (Holland)
Menzel S.	53.19	Oak, manzanita, pine	-	Primary, not classified
Menzel N.	53.19	Chamise with some ceanothus and manz.	-	Primary (Aiken)
Monterey no. 1	8.49	Chamise	22.3	Old valley-fill material (Lockwood)
Monterey no. 2	9.59	Wild cherry	34.0	Old valley-fill material (Lockwood)
Manzanita Gleason	51.68	Manzanita	-	Primary, volcanic
Oregon Oaks	68.53	Scrub oak (Ore. Oak)	8.6	Primary (Aiken)
Redding	67.27	Manzanita, some pine	-	Old valley-fill material (Redding)
Tulare	28.79	Oak, buckeye, ceanothus	32.0	Primary, granitic (Holland)
Ukiah	30.05	Oak, manzanita	33.1	Primary (Hugo)
Gleason no. 3	39.86	Manzanita	24.1	Primary (Gleason)

[a] These are not average rainfall figures for the localities, but are the amounts at the plots for the year for which the soil moisture was recorded for the first year after burning. In some cases, this rainfall is much higher than the mean annual in some cases.

given in Table 1. They were selected to give a wide variety of vegetative types, rainfall patterns, topography, and soils. At all of the sites the rain generally fell from October through March; most of it in December, January, and February. Temperatures during the winter usually were too low for plant growth which did not start until early spring, generally just before the rainy season was ended. The growth of the plants, therefore, was dependent to a very large extent upon the amount of water that could be stored in the soil mantle.

Following the fire, grasses and forbs usually succeeded the brush, but with some brush species, several annual burnings were necessary before they were eliminated. The burned plots were not reseeded to grasses as generally would be the approved practice in burning for forage production, since one of the objectives of the studies was to observe the succession of vegetation.

The brush was cut, piled on the plot, and burned, but the surface of the soil was not disturbed any more than necessary to do this work. In subsequent years, any resprouting vegetation was cut, a torch was applied over the entire surface, and, of course, the aerial parts of the grasses and forbs were also killed without destroying the roots. This resulted in a more complete removal of the vegetation than is generally possible under broadcast burning, but the soil did not remain bare throughout the year; either the brush resprouted, or grasses and forbs grew. As the plots were repeatedly burned for several years, the brush species disappeared.

Soil samples were taken to the full depth of the primary soils, the soil tube being driven to bedrock. On some of the old valley-filling material, it was only possible to sample to a depth of 30 inches.

The total water-storage capacities of the soils given in Table 2 range from 5.5 to 10.8 inches, and suggest that soil storage as a factor in holding back enough water to prevent flooding

Table 2--The excess of water in storage in the soil in the burned plots over that in the unburned before the winter rains began in the fall of the first year after burning

Plot	Total moisture capacity[a]	Per cent of total capacity	Amount
	inch		inch
Button Canyon	6.4	1.6	0.1
Cold Fork	5.7	36.8	2.1
Ceanothus Gleason	6.7	16.4	1.1
Corning	5.5	32.7	1.8
Diamond Range	6.7	10.4	0.7
Holland	7.6	35.5	2.7
Inskip	10.0	7.0	0.7
Lake	6.2	22.6	1.4
Madera no. 1	8.9	7.9	0.7
Madera no. 2	9.1	16.5	1.5
Menzel South	7.1	22.5	1.6
Menzel North	7.3	8.2	0.6
Monterey no. 1	10.8	7.4	0.8
Monterey no. 2	9.5	28.4	2.7
Manzanita Gleason	9.7	9.3	0.9
Oregon Oaks	7.4	6.7	0.5
Redding	6.0	10.0	0.6
Tulare	8.8	17.0	1.5
Ukiah	7.2	25.0	1.8
Gleason no. 3	5.5	12.7	0.7

[a] The amount of water that can be stored in the soil for use by plants, the difference between maximum and minimum soil-moisture contents to the depth sampled.

is not important. The conclusion reached by LYNCH [1939] that "A rainfall of eight inches in ten days, of which the last day yields 2.5 or more inches, results in heavy floods," which indicates that the soil can store about six inches before floods occur, is in substantial agreement with the amounts of water required to prime the soil used in these experiments when covered with brush.

The excess water in storage in the soil in the burned plots over that in the unburned before the winter rains began in the fall of the first year after burning is given in Table 2 in inches and in per cent of the total amount of water that can be stored in the soil. At this time the soil moisture is at the lowest level for the season.

While the moisture in storage in the soil on the burned plots just before the beginning of the rainy season was greater than in the unburned, in some cases, it was small. These are Button Canyon, Diamond Range, Gleason no. 3, Inskip, Madera no. 1, Manzanita Gleason, Menzel North, Oregon Oaks, and Redding. On these plots the brush resprouted or large broad-leafed species succeeded the original brush plants. On the Button Canyon, Menzel North, and Gleason no. 3 plots the chamise revegetated the area during the first season following the burn. On the Oregon Oaks, Manzanita Gleason, and Diamond Range plots the oaks resprouted. The burned Inskip and Madera no. 1 plots were invaded with tall growing species. The Inskip burned plot was revegetated the first year after the burn by stump sprouting Manzanita, horehound, oaks, and yerba santa. The Madera burned plot had yerba santa, globe mallow, and some resprouted oak and ceanothus. Very little grass grew on these plots the first year. On the Redding burned plot many of the woody species resprouted. On all of these plots a stand of grass was not obtained the first year. The gradual replacement of brush with grasses and forbs following repeated burning is illustrated by the records for the Button Canyon plots. Although the excess water in the burned plot was only 0.1 inch at the end of the first season, it increased to 1.0 inch in the second year, to 1.6 inches in the eighth year and 2.4 inches at the end of the ninth year, or 37.5 pct of the total water that could be stored in this soil. The chamise had been almost entirely killed out by this time and replaced largely by grasses, red brome, downy chess, slender oat, fescue, and chess together with redstem filaree, broadleaf filaree, and a few other forbs. Figure 1 shows the condition of the soil just after burning in the Button Canyon plot. Figure 2 is the same plot at the end of the first growing season after burning showing the heavy growth of the resprouted chamise. Figure 3 is the same plot after the ninth annual burning. The almost complete removal of the brush and its substitution by grasses and forbs has occurred by this time.

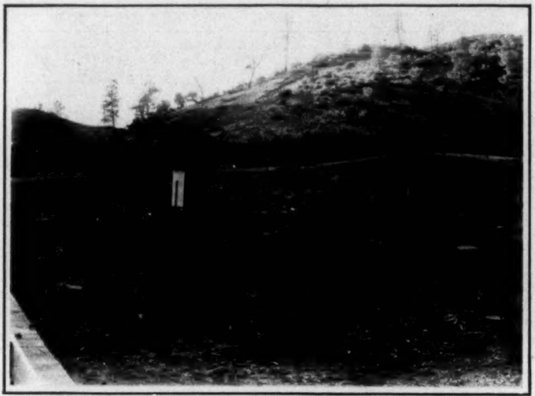

Fig. 1--Button Canyon plot after the first burning

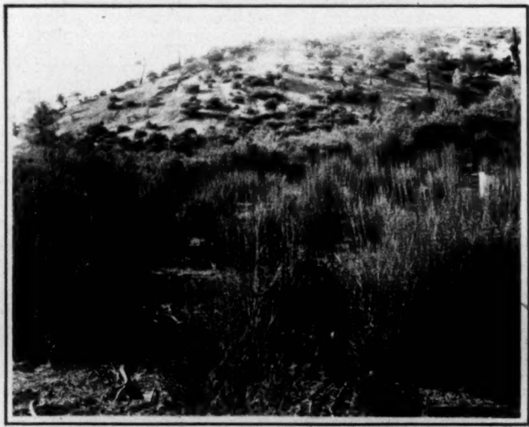

Fig. 2--Button Canyon plot at the end of the first season after burning; the chamise resprouted and made rapid growth

The soil-moisture conditions in the burned and unburned Button Canyon plots for the first season are shown in Figure 4. Those in the same plots during the ninth year are given in Figure 5. During the first year the soil moistures in the burned and unburned plots were quite similar. The moisture extraction curves (Fig. 4) show that there was a lag in the extraction of water from the burned plots in the early part of the summer, but as the resprouted chamise increased in size it depleted the supply of moisture so that the moisture content of the soil in both plots was reduced to the same level as that just after the burning in the previous fall.

The moisture conditions in Figure 5, in which only the total supply in the full depth of the soil is shown, are decidedly different. Here there was a carry-over of moisture from the previous

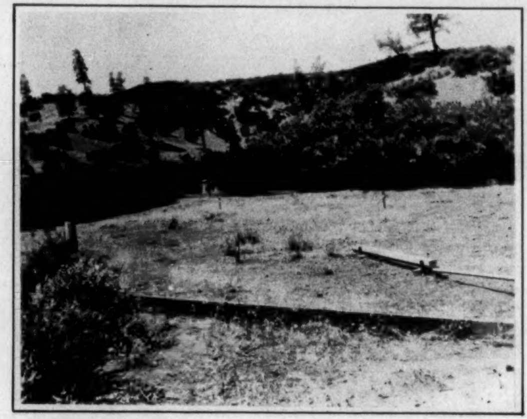

Fig. 3--Button Canyon plot after the ninth annual burning; there has been an almost complete replacement of chamise by grasses and forbs

season in the burned plot as shown in November. It should be noted that the moisture in this plot was not at the permanent wilting percentage while in the unburned it was slightly below and this was repeated in September of the next year.

The Manzanita Gleason plot record is a further illustration of the fact that the differences in soil moisture are a reflection of the kind of vegetation which grew following the burning. Here the excess moisture in the burned plot over the unburned was only 0.9 inch the first year after burning when the site was taken over by oak scrubs as shown in Figure 6. At the end of the second year, however, when the second burn removed these and grasses invaded the area, the difference between burned and unburned plots amounted to 1.6 inches or 21.9 pct of the total storage capacity of the soil. The burned Oregon Oaks plots showed an excess of 1.0 inch and the Redding plots 1.4 inches of water at the end of the second year following two annual burnings over the unburned. The excess moisture in the burned Monterey no. 1 plot over the unburned was only 0.8 inch at the first year after burning, but this increased to 1.8 inches in the fourth year.

The moisture records from the Monterey no. 2 plots are shown for one season in Figure 7. Here the cover is mostly wild cherry. The burned plot was covered with grasses consisting of Howell bluegrass, rat-tail fescue, red brome, native annual fescue, and soft chess with a large number of forbs with Indian lettuce and nievitas the most plentiful. The rainfall was low at this site, 9.59 inches. Hence some of the differences in soil moisture may be due to the large portion of the rain intercepted by the dense stand of wild cherry. The throughfall of rain in the unburned plot was not sufficient to wet the entire soil profile whereas it did in the burned. The contrast in amounts of water in storage in the soil at the end of the season is marked, amounting to an excess of 2.7 inches in the burned plot over the unburned. The maximum difference was obtained in the Cold Fork plots where after two annual burns the burned plot had 3.6 inches more water in the soil profile at the end of the season than in the unburned. This is 63.2 pct of the total storage capacity of the soil.

The soil in every unburned plot was reduced to the permanent wilting percentage to the full depth sampled. Figure 8 is the record from the Menzel North unburned plot. Figure 9 is that for the Corning plot. The record of soil moisture in six-inch depths for the Button Canyon plots is shown in Figure 10. But where the original brush was replaced by grasses and forbs, the soil moisture throughout the full depth was not used and there was water left in storage in the soil at the end of the growing season before the winter rains started. Since there is less water required to reprime the soil reservoir during the following rainy season, a saving of water is effected, the

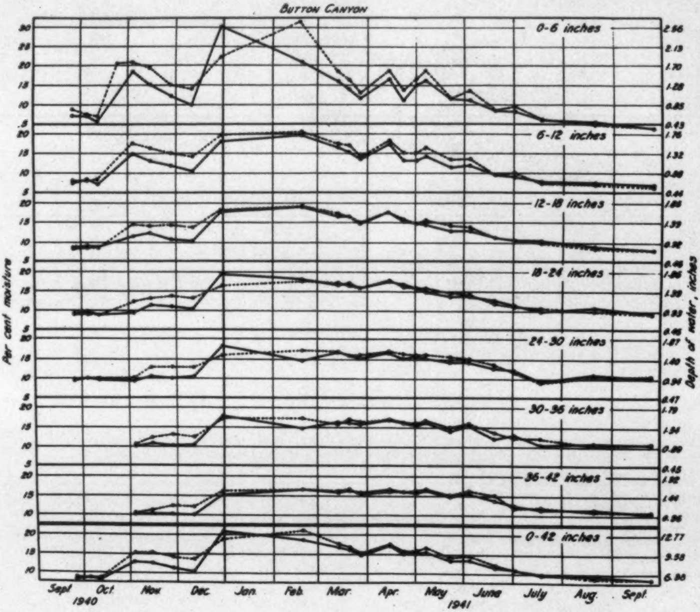

Fig. 4--Soil moisture in the Button Canyon plots, the first year after burning; the burned plot record is the dotted line; the unburned, the solid line

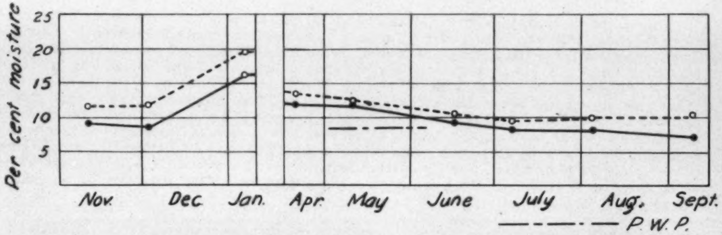

Fig. 5--The moisture content of the soil to a depth of four feet in the Button Canyon plots the ninth year after burning; the record for the burned plot is the dotted line; that for the unburned is the solid line; P.W.P. is permanent wilting percentage

excess either appearing as surface runoff or as underground flow. In the localities where these studies were conducted, there has been little difference in surface runoff between the burned and

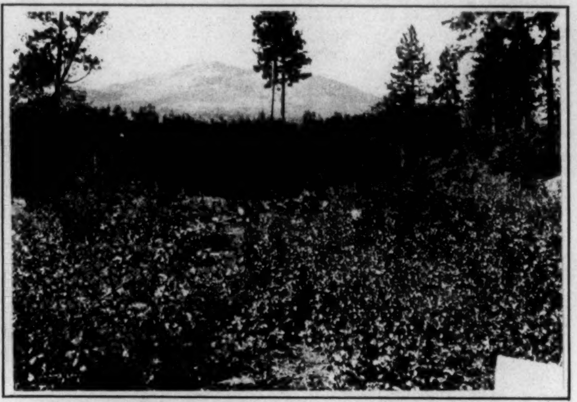

Fig. 6--Regrowth of resprouted brush on the Manzanita Gleason plot at the end of the first season following the burning

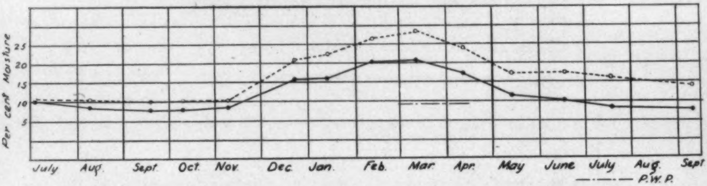

Fig. 7--The moisture content of the soil to a depth of four feet in the Monterey plots the first year after burning; the record for the burned plot is the dotted line and that for the unburned, the solid line

unburned areas, as measured from plots 50 × 50 ft. The runoff has been on the average for all of the plots only about six per cent of the rainfall so that the subsurface flow greatly exceeded the surface runoff.

The interception of rain by the brush on the unburned plots as measured in trough gages placed under the plants has been a large portion of the total rainfall, amounting to about 20 pct. This represents a difference in catch of rain in standard gages in the open on the bare plots and the trough gages under the plants. It is the throughfall as defined by HAMILTON and ROWE [1949]. These investigators have measured the loss of rainfall which is retained by the aerial portion of the vegetation and is either absorbed by it or returned to the atmosphere through evaporation. They call this interception loss and estimate it to be five to 11 pct of the annual precipitation.

The soil-moisture records show that the soil to the full depth was wetted as early in the season in the burned plots as in the unburned ones, and in many cases earlier in the unburned ones as indicated in Figures 4, 5, and 7. This may be due to the difference in amounts of water reaching the ground because of the interception, but it does indicate that the ability of the soil in the burned plots to absorb water has not been impaired by burning; otherwise there would be a noticeable lag in time taken to wet the burned soil as compared to the unburned. Samples were taken in a number of cases very soon after the rains occurred. The absence of appreciable differences in runoff between the plots is further evidence for this statement.

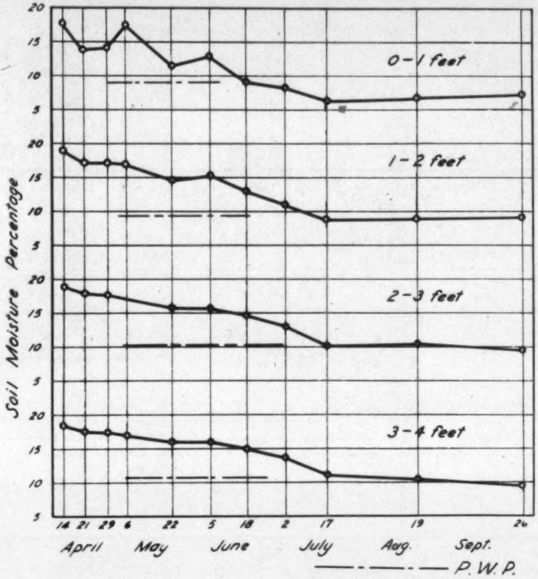

Fig. 8-- Soil moisture in the unburned Menzel North plot

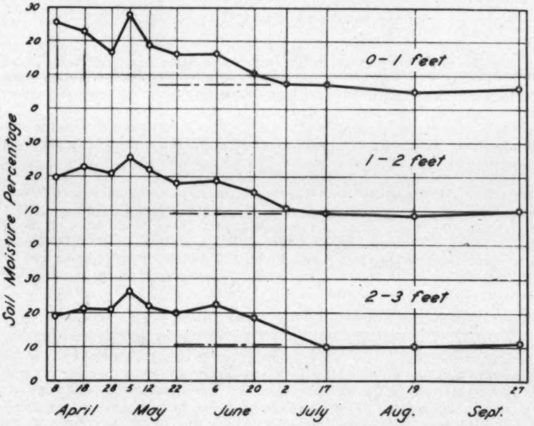

Fig. 9--Soil moisture in the unburned Corning plot

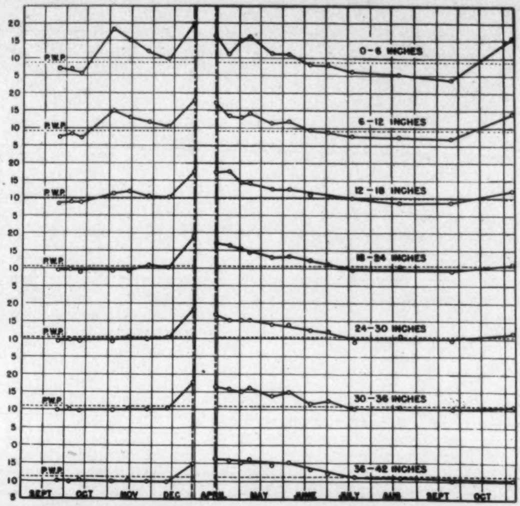

Fig. 10--Soil moisture in the unburned Button Canyon plot; the dotted horizontal lines are the permanent wilting percentages as determined in the laboratory

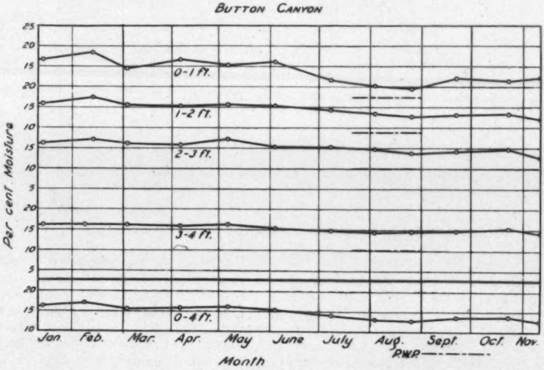

Fig. 11--Soil moisture in Button Canyon sterilized plot

The fact that the stored water in the unburned plots was depleted and not in the burned when the brush species were removed led to a study of the soil moisture in plots which were sterilized by applying sodium borate. These plots were approximately 50 × 50 ft and were adjacent to the

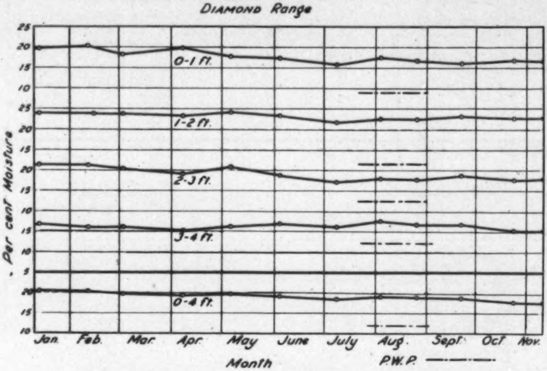

Fig. 12--Soil moisture in the Diamond Range sterilized plot

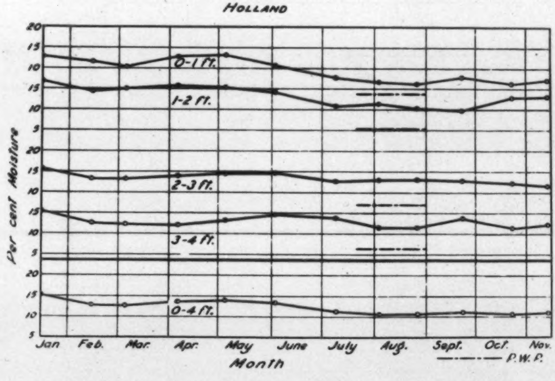

Fig. 13--Soil moisture in the Holland sterilized plot

unburned plot on which the original cover was not disturbed. It was hoped to eliminate all losses through transpiration, but this was not actually accomplished in all of the plots. Even though the samples were taken in the center of the plot, live roots of trees and brush were encountered occasionally in sampling. Figures 11, 12, 13, and 14 give the records for a typical year for each of the areas tested. The contrast between the moisture conditions under the almost complete absence of transpiration and that under brush is striking, for example, compare those shown in Figure 10 to those in Figure 11, adjacent plots. In no case was the soil in the foot-depths sampled reduced to the permanent wilting percentage. The moisture content of the top six inches, however, was reduced to the permanent wilting percentage. It is clear that the losses are confined largely to the upper foot of soil.

A further study of transpiration losses of moisture as compared to evaporation was made by growing an Allepo pine tree (Pinus halepensis) in a large tank holding about a ton of soil. The

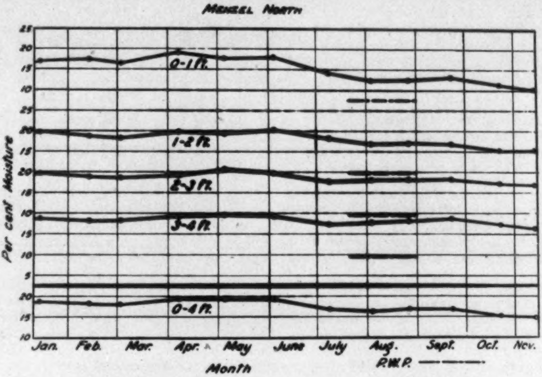

Fig. 14--Soil moisture in the Menzel North sterilized plot

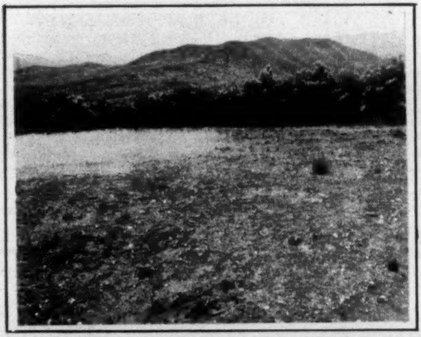

Fig. 15--Grasses in the middle and bare areas around edges due to competition of chamise plants

tree was planted on March 26, 1935, and cut off just above ground level on November 8, 1940, when the tree weighed 50 lb and the needles 11.8 lb. It was eight feet high and had a spread of six feet. A tight-fitting metal cover was placed over the tank with an opening for the trunk of the tree on December 12, 1935, and was kept there until the tree was cut down. An opening was provided to permit the application of water and to sample the soil. The tank was suspended in such a way an automatic record was obtained of the loss of water from the system. All openings in the cover were plugged with cotton to prevent evaporation losses. The tree transpired on an average of 15 lb of water a day for the summer of 1940.

The record of the loss of water from a tank with a bare soil surface under similar climatic conditions to those under which the pine tree was grown affords a comparison of transpiration and evaporation losses. This tank contained a soil of slightly finer texture than that used for the pine tree. It was a Yolo clay loam with a moisture equivalent of 22.2 pct. The pine tree was grown on a Yolo fine sandy loam with a moisture equivalent of 16.8 pct. The tank was irrigated and the surface of the soil was undisturbed except to pull the weeds which started to grow. The tank was weighed to keep a record of the water lost, but was covered before each rain to prevent addition of water after the initial wetting. The tank was kept for 1547 days and the loss averaged 0.037 lb per day for the entire period. The soil below the top foot was not reduced to the permanent wilting percentage even after such a long exposure to evaporation. Of the total loss of 57 lb of water by evaporation, 12 lb were lost the first week, 22 lb at the end of the first month, and 35 lb for the first year. The pine tree used as much water in less than four days by transpiration as the bare soil lost by evaporation in over four years.

An example of the competition of brush (chamise) for water against grass is shown in Figure 15. The grass in the middle of one of the 50 × 50 ft plots has grown, but around the edges of the plot the soil is bare because of the extraction of water by the adjacent brush and the inability of the grasses to compete with it for water.

Summary--The conditions under which these experiments were conducted where the rainfall generally fell from October through March permitted long periods of observation of soil-moisture changes during the growing season because of evaporation and transpiration without the complication of those brought about by additions of water to the soil by rain. The growth of the vegetation on the plots, furthermore, was dependent largely on the water which could be stored in the soil during the winter.

In every case the soil moisture in the plots on which the original vegetation was undisturbed used all of the moisture available for plant growth to the full depth of soil sampled. On the burned plots this was not the case. In the areas where the brush resprouted and grew rapidly there were slight differences in the amount of moisture in the soil at the end of the growing season. This condition existed even after several annual burnings on some of the plots, but where the brush was finally replaced with grasses and forbs, there were appreciably larger amounts of water remaining in the plots that were burned than in the unburned. The excess water in the burned plots is dependent upon the kind of vegetation which grew subsequent to burning. The extraction of water depends upon the ability of the plants to extend their roots to the full depth of soil and upon the persistency of the plants throughout the growing season. Although some of the annual grasses may have been deep rooted enough to penetrate the full depth of soil, their early maturity and death eliminated the draft on the soil-moisture supply during the forepart of the season so that some available water was left in the soil. Even where perennial grasses grew on the burned areas, their use of water was not as great as that of brush. In general, the differences in the surface layers were small whether the plots were burned or not, but the establishment of grasses and forbs on the burned areas resulted in more water remaining in storage in them than in the unburned. Savings in water would then be accomplished by burning since less water would be required to reprime the watershed during the following rainy season and the excess would appear as surface or underground flow.

The removal of all vegetation would result in the maximum saving as indicated by the results in the sterilized plots where almost all transpiration was eliminated. The losses by evaporation directly from the soil surface are small compared to transpiration and the water use by grasses and forbs was less than by the brush.

The soil-moisture records show that the soil in the burned areas was wet as early and in many cases earlier than in the unburned ones, thus indicating that the permeability of the soil for water was not adversely affected by burning.

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Transactions, American Geophysical Union Volume 34, Number 2 April 1953

CORRELATION BETWEEN PIPE FLOW AND UNIFORM FLOW IN A TRIANGULAR OPEN CHANNEL

W. M. Owen

Abstract--A dimensionless open-channel resistance diagram based on an existing diagram given by Moody for circular pipes is presented. Data was taken on a 90-degree triangular flume in smooth and roughened condition from actual open-channel flow data. A comparison of the two diagrams presented is made by computing average velocities for several hypothetical channels. Correlation was found to be fair.

Introduction--Knowledge of the flow characteristics such as energy loss and velocity distribution for flow in open channels is in a much less satisfactory state than exists in closed conduits. The reason for this condition is that the experimental work in open-channel flow is infinitely more exacting and requires a much more elaborate apparatus. Laboratory investigations of open-channel flow are also necessarily limited in range of variables and thus do not approximate the conditions found in large open channels such as rivers. It is desirable, therefore, to be able to apply the data accumulated from pipe flow to determine the various flow characteristics for open channels. In order to establish a correlation between open-channel and closed-conduit flow, some reliable data had to be obtained for a given open channel. The tests reported herein were conducted for this purpose.

If we assume that the average velocity of the flow of a liquid in an open channel is a function of the following variables: R, the hydraulic radius; S, the slope of the channel; μ, the viscosity of the fluid; ρ, the mass density of the fluid; e, a measure of the roughness of the channel; g, the acceleration of gravity; and β, a dimensionless shape factor dependent on the cross-sectional shape, then dimensional analysis reveals that the average velocity may be expressed by an equation of the form

$$V = \sqrt{gRS}\ \phi\left[(R/\nu)\sqrt{gRS},\ e/R,\ \beta\right]$$

or

$$V/\sqrt{gRS} = \phi\left[(R/\nu)\sqrt{gRS},\ e/R,\ \beta\right]$$

where $\nu = \mu/\rho$.

The data used for making Figure 1 were obtained from the graph showing the relation between friction factor and Reynolds number presented by MOODY [1944]. The relations used in making these

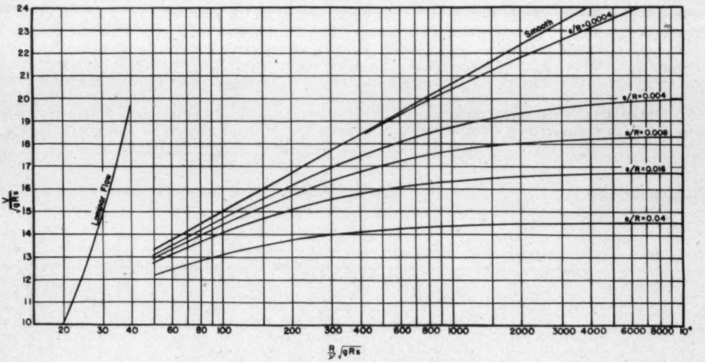

Fig. 1--Graph of dimensionless variables transformations are as follows

$$V/\sqrt{gRS} = \sqrt{8/f} \quad \text{and} \quad N_R\sqrt{f}/8\sqrt{2} = (R/\nu)\sqrt{gRS}$$

where $N_R = 4VR/\nu$. The reason for using these dimensionless variables instead of the variables used in the Moody graph is that in open-channel work it is usually the velocity which is unknown, whereas in pipe flow the velocity is known and it is usually required to find the head loss.

The purpose of this investigation was to obtain by experiment a set of curves similar to that of Figure 1 for flow in an open channel and to compare these curves with those obtained from the pipe-flow diagram. In order to eliminate the effect of the fourth dimensionless variable, β, a channel of triangular cross-sections was used so that the cross-sectional form would remain constant for all test conditions.

In order to obtain a range of values of the dimensionless variable e/R, it was decided to roughen the channel by cementing uniform sand grains to the smooth plywood surface.

Tests were run with variable depths for three slopes, 0.0005, 0.0010, and 0.0020, for each of the three surface roughnesses, smooth, small sand grains (0.00125 ft diameter), and large sand grains (0.00250 ft diameter).

The following symbols are used in this paper.

V = average velocity of flow, ft/sec
y = depth of water in channel, ft
R = hydraulic radius (equal to $2\sqrt{2}\,y$ for 90-degree triangular channel)
Q = volume rate of flow, ft^3/sec
e = channel roughness (equal to the diameter of the sand grains in this paper), ft
S = channel slope
μ = dynamic viscosity of fluid, lb sec/ft^2
ρ = density of fluid, lb sec^2/ft^4
$\nu = \mu/\rho$ = kinematic viscosity, ft^2/sec
g = acceleration of gravity, ft/sec^2

Description of apparatus--Water entered the reservoir (see Fig. 2, left end) through the four-inch standpipe supply line. Water in the standpipe supply line was under a constant head of approximately 45 ft. A gravel baffle located in the reservoir prevented large-scale eddies from entering the test channel. After passing through the gravel baffle the water then entered the head bay, which was fitted with a sheet-metal transition section to guide the water into the test channel with a minimum of disturbance.

The channel itself was 55.3 ft long. It was supported by the reservoir and seven additional supports spaced approximately eight feet apart. The channel was set at a given slope by adjusting the leveling screws at each of the supports. Several adjustments and checks by means of a surveyor's level were required for each setting of the slope. After the final adjustment, variations in the elevation of the channel bed from the mean slope line of approximately 0.02 inch were noted.

The depth of water in the channel was controlled by means of an end gate. Water depths in the channel were measured by means of electric point gages at eight points five feet apart starting 16

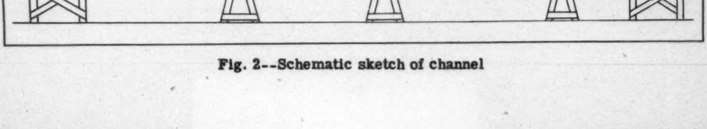
4'
55.3'
Standpipe Supply Line
Gravel Baffle
8'
7 Supports Spaced at 8 Ft Intervals
8 Point Gages Spaced at 5 Ft Intervals
2'
A
A
Tail Gate
Section A-A

Fig. 2--Schematic sketch of channel

ft from the entrance to the channel. After passing over the tail gate the water was discharged to a tank mounted on scales. The weighing tank had a capacity of 15,000 pounds.

The channel was made of 3/4-inch waterproof plywood supported by means of a welded steel framework. The plywood was sanded and given several coats of waterproof varnish so that it presented a smooth continuous surface over the entire length. In order to roughen the channel, the smooth channel was given another coat of varnish and uniform sand grains were sprinkled on the surface before the varnish hardened. A second coat of varnish was placed over the surface after the first coat dried to further fix the sand grains to the surface. Care was taken to make sure that the sand-grain distribution was as uniform as possible. Figure 3 shows photographs of a portion of the small and large sand-grain surfaces. High-grade Ottawa sand was used. The small grains used were those which passed through a 40-mesh sieve and were retained on a 45-mesh sieve. The large sand grains were those which passed through a 20-mesh sieve and were retained on a 25-mesh sieve. This gives as an average diameter 0.00125 and 0.00250 ft for the small and large grains, respectively.

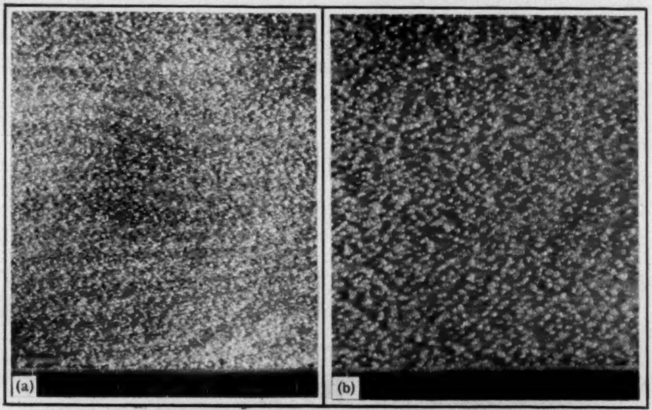

Fig. 3--Views of the surface of the channel; (a) small-grain surfaces, and (b) large-grain surfaces; note scale in inches at bottom

The procedure used in the tests was as follows: Water was admitted to the channel at a low rate of flow and the tail gate was then adjusted to give what appeared to the eye to be uniform flow. The eight electric point gages were then set to read the elevation of the water surface. The readings of the eight point gages were then compared and adjustments made to the tail gate to correct for the non-uniformity of the flow. Usually it took a minimum of six adjustments of the tail gate to produce uniform flow. At the higher discharges when appreciable waves formed on the surface of the channel the tail gate could not be adjusted so that the point gages all read the same. The flow was accepted as uniform when the average depth at the four upstream gages was equal to the average depth at the four downstream point gages. Having obtained uniform flow in this manner, the readings of the point gages were then recorded. The discharge was then measured by determining the time necessary to collect a given quantity of fluid in a tank mounted on a calibrated scale.

The discharge was then increased by a small amount and the above process repeated. A graph showing the relation between $V/\sqrt{gRS}$ and $(R/\nu)\sqrt{gRS}$ was made while the data were collected, and test runs were spaced to give a fairly even distribution of data throughout the range of test conditions. After a complete range of depths for one slope and surface condition, the channel slope was changed and the tests repeated.

Results of tests--The results of the tests described herein are shown graphically in Figures 4-6.

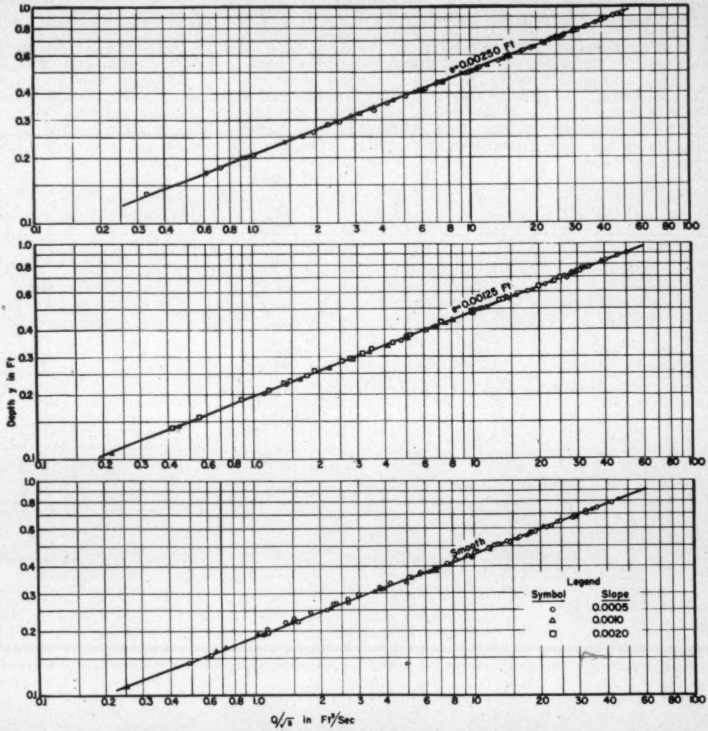

Fig. 4--Results of tests, relationship of depth to $Q/\sqrt{s}$

Curves showing the relation between $V/\sqrt{gRS}$ and $(R/\nu)\sqrt{gRS}$ for various values of e/R similar to the curves taken from pipe-flow data (see Fig. 1) could not be plotted directly from the data taken in this investigation because of the variation of e/R with depth. It was decided to plot log-log graphs showing the relation between the depth y and $Q/\sqrt{S}$ (Fig. 4). Dimensional analysis indicated that by using these variables a relation of the following type would result, if viscosity is neglected.

$$y = (Q^{0.4}/\sqrt{gS})\, f\,(e, Q, gS)$$

Since the lines in Figure 4 are straight, a power-law relation is indicated. The most general dimensionally homogeneous relation of this type is

$$y = Ae^{1-2.5n}\, Q^{n}/\sqrt{gS} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where n and A are constants that do not depend on the roughness or nature of flow.

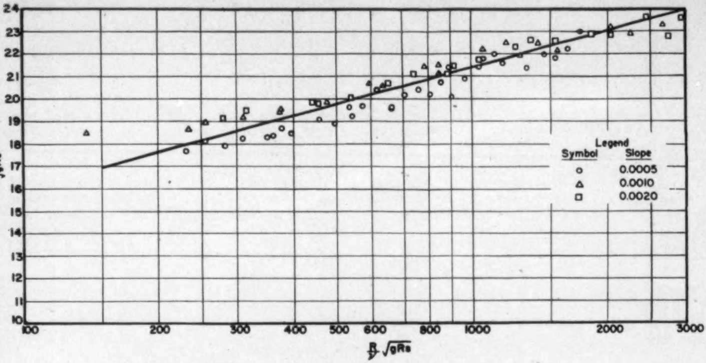

Fig. 5--Results in dimensionless form for the smooth condition

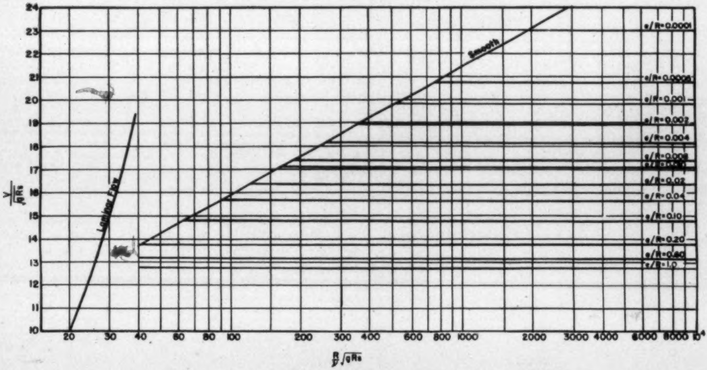

Fig. 6--Relationship between $V/\sqrt{gRS}$ and $(R/\nu)\sqrt{gRS}$

The value of n is equal to the slope of the curves showing the relation between y and $Q/\sqrt{S}$ (Fig. 4) for the small and large sand-grain data. The values of the slopes for the small and large sand-grain data were 0.389 and 0.392 respectively. It was decided to use a value of $n = 0.390$ for both the large and small sand-grain data in all subsequent calculations. Using this value of n, the value of the constant A was then determined from the small and large sand-grain data. The values of A were 0.454 and 0.466 for the small and large sand grains, respectively. The fact that these two sets of test data did not agree on the value of the constant A indicates that the roughnesses were not geometrically similar. This may have been caused by the difference in spacing of the sand grains or by the fact that the varnish in which the sand grains were embedded tended to fill in the space between the small sand grains and thus present a smoother surface than was intended. It was decided to use a value of A equal to 0.466 since it was felt that the large sand grains approached more nearly the NIKURADSE [1933] sand-grain pattern.

Having obtained the values of n and A in the preceding manner, (1) was then used to construct a curve similar to Figure 1. The following relation may be derived directly from (1).

$$\left.\begin{aligned} V/\sqrt{gRS} &= 1/8\,(2\,\sqrt{2}/A)^{1/n}\,(e/R)^{2.5-1/n} \\ \text{or}\qquad V/\sqrt{gRS} &= K\,(e/R)^{2.5-1/n} \end{aligned}\right\}\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where K was found to be 12.74.

Figure 6 is a semi-log graph showing the relation between $V/\sqrt{gRS}$ and $(R/\nu)\sqrt{gRS}$ based on (2) and the average curve for the data taken with the triangular flume in the smooth condition (Fig. 5).

For the purpose of comparison, several velocities in each of two 90-degree triangular channels whose relative roughnesses are 0.008 and 0.04, respectively, and whose slopes are 0.001, were computed using both Figures 1 and 6. The results of these computations are shown in Table 1.

Table 1--Comparison of velocities obtained by using Figures 1 and 6; slope = 0.001; $1/\nu$ = 100,000

Depth y	Hyd. radius R	$(R/\nu)\sqrt{gRS}$	e/R = 0.008			e/R = 0.04		
			V		Variation of Owen from Moody	V		Variation of Owen from Moody
			By Fig. 1 (Moody)	By Fig. 6 (Owen)		By Fig. 1 (Moody)	By Fig. 6 (Owen)	
ft	ft		ft	ft	pct	ft	ft	pct
0.2	0.0707	341	0.789	0.828	+5.0	0.670	0.745	+10
0.4	0.1414	952	1.19	1.17	-1.7	0.968	1.05	+ 8.1
0.6	0.212	1740	1.49	1.44	-3.4	1.20	1.30	+ 7.7
0.8	0.283	2690	1.73	1.66	-4.2	1.38	1.49	+ 7.5
1.0	0.353	3770	1.95	1.86	-4.6	1.55	1.67	+ 7.2
1.2	0.424	4940	2.44	2.03	-4.9	1.70	1.83	+ 7.3

The results shown in Table 1 indicate that velocities for open channel of triangular shape may be determined with an accuracy of ten per cent by using the dimensionless curves (Fig. 1) which are based on Moody's pipe-flow diagram.

These results, while indicative of the close correlation between closed conduit and open-channel flow, are not conclusive. Because of the uniform nature of the roughness in the channel used in this investigation, it was felt that perhaps the curves shown in Figure 6 would be in better agreement with the curves of Nikuradse than those of Moody (Fig. 1). Figure 7 is a graph showing the relationship between the variables $V/\sqrt{gRS}$ and $(R/\nu)\sqrt{gRS}$ for a given value of the relative

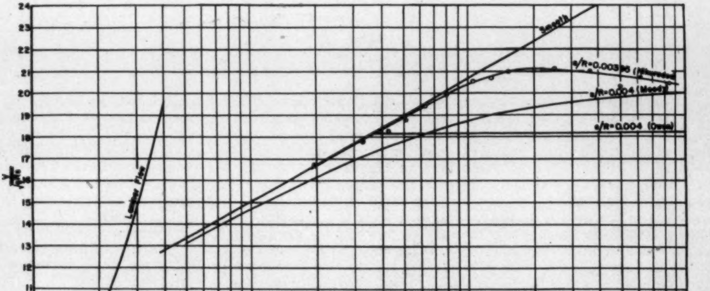

Fig. 7--Dimensionless relation for a given value of roughness, comparing Nikuradse, Moody, and Owen curves roughness. It is apparent from this diagram that the data reported herein did not agree with the Nikuradse data as well as with that presented by Moody.

In spite of the care taken in collecting the data, it was not possible to eliminate the scatter in the data as is shown in Figure 5. The range of variables obtainable in this investigation was also smaller than was desired. In order to establish definitely a correlation between open-channel and closed-conduit flow, an open channel of considerably greater length and cross-sectional dimension would be required.

Acknowledgments--The work presented in this paper was carried out in the Hydraulics Laboratory of the Department of Theoretical and Applied Mechanics as part of the work of the Engineering Experiment Station in the College of Engineering of the University of Illinois.

Acknowledgment is due to H. L. Langhaar, under whose direction the work was performed, and also to A. A. Bjelland and R. L. Watson, who carried out a portion of the work as a thesis project. Special acknowledgment is also due W. D. Mitchell, Hydraulic Engineer with the U. S. Geological Survey, for his helpful suggestions.

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ANOMALOUS GLACIAL DEPOSITS IN THE COLORADO FRONT RANGE AREA, COLORADO

Ronald L. Ives

Abstract--Reinvestigation of reported glacial deposits in the Colorado Front Range area, in locations above or exterior to those commonly classed as glaciated, has resulted in a doubling of the number of known deposits, and the finding of a rough gradation from glacial, near the Arapaho Massif; through reworked glacial, at distances of six or seven miles; to glacio-fluviatile and fluviatile at greater distances. From this evidence, one or more early Pleistocene glaciations are postulated, the parent ice body being of the ice-cap type, resting upon a gently rolling terrain of which only the so-called peneplain surfaces now remain. A similar large ice cap in the Laramie-Poudre area is suggested by scattered evidence between those rivers and the Laramie-Fort Collins highway.

Introduction

About 20 years ago, it appeared that the physiographic history of the Colorado Front Range was almost completely solved. Many geologists of that time believed that the Front Range initially consisted of two uplifted peneplains, one Eocene and one Miocene (with a few remnant elevations), which had never been glaciated. These peneplains had twice been incised by glaciers, once in the early Pleistocene, and once in the late, producing the present terrain, with the assistance of slight post-glacial erosion. There were, it is true, a few minor scraps of evidence which did not fit into this picture, but only a few weeks of field work, it was believed, were necessary to solve the history completely.

Today, the physiographic history of the Colorado Front Range is not so certainly known. Geologists of various schools recognize from one to eight or more upper surfaces, which may have been created by peneplanation [VAN TUYL and LOVERING, 1935]; differential erosion [WAHLSTROM, 1947]; faulting [IVES, 1941]; or some combination of these. This upland terrain complex has been deeply trenched by stream and glacial erosion, much or all of it during the later Pleistocene, and occurring during six or more glacial stages [BRYAN and RAY, 1940; IVES, 1938 and 1952; JONES and QUAM, 1944; RAY, 1940], some regarded as major, and some as minor. There still remains some evidence, supposedly glacial or periglacial, which remains to be accounted for. A part of this evidence is the subject of this paper.

Nature and distribution of evidence

General locations--During the time that the number of recognized glacial advances in the Colorado Front Range area was being increased from two to six or more, a large number of field workers found deposits of glacial-appearing material in areas not physiographically related to the recognized glaciated areas. Some of this was atop the supposedly unglaciated peneplains; more was found exterior to the glaciated areas, sometimes by several miles. General location of these anomalous deposits is indicated in Figure 1.

Description of the deposits in the Lakewood area comprises the major part of this paper. Anomalous deposits in the Colorado Headwaters area have been outlined in a previous report [IVES, 1942], and will be fully described in a forthcoming paper. The Prairie Divide glacial deposits have been outlined by BRYAN and RAY [1940], but their apparent extent far exceeds the original description. Further study of the Poudre Bench and Glendevey deposits, to determine their full extent, seems desirable before description and evaluation are attempted.

Within the Lakewood area, deposits classed as glacial, with varying degrees of confidence, are numerous. Locations of these are shown in Figure 2, an outline map based on the U. S. Forest Service base for the Arapaho National Forest, 1940. Area covered by Figure 2 is substantially that designated by 16 in ATWOOD and ATWOOD [1938], Figure 1, but the present writer finds the field evidence more extensive, but less conclusive, than did the Atwoods.

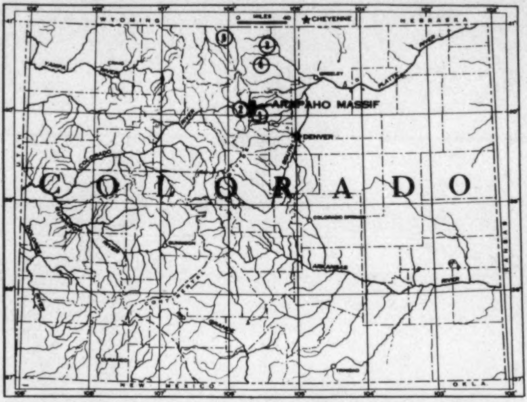
WYOMING
NEBRASKA
CHEYENNE
MILES
0
40
ARAPAHO MASSIF
DENVER
COLORADO
NEW MEXICO
OKLA
①
②
③
④
⑤

Fig. 1--General location of anomalous glacial deposits and their relation to the Arapaho Massif; (1) Lakewood area, (2) Colorado Headwaters area, (3) Prairie Divide area, (4) Poudre Bench area, and (5) Glendevey area

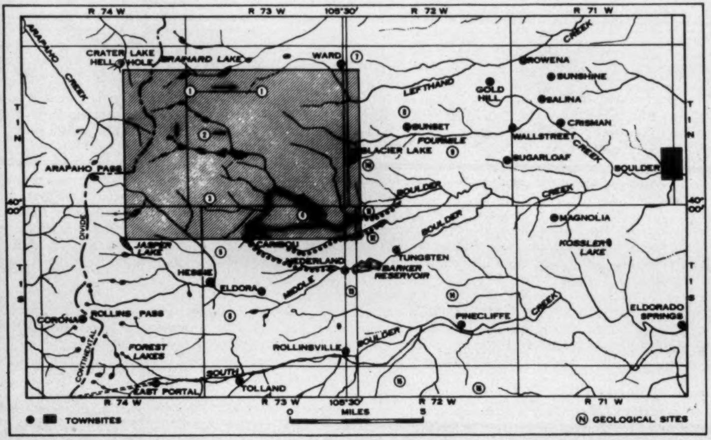
R 74 W
R 73 W
105°30'
R 72 W
R 71 W
ARAPAHO CREEK
CRATER LAKE
HELL HOLE
BRAINARD LAKE
WARD
LEFTHAND
GOLD HILL
ROWENA
SUNSHINE
SALINA
CRISMAN
SUNSET
FOURMILE
WALLSTREET
CREEK
GLACIER LAKE
SUGARLOAF
BOULDER
ARAPAHO PASS
40° 00'
BOULDER CREEK
MAGNOLIA
KOSSLER LAKE
DIVIDE
JASPER LAKE
CARIBOU
NEDERLAND
TUNGSTEN
BARKER RESERVOIR
HESSIE
ELDORA
MIDDLE
CORONA
ROLLINS PASS
PINECLIFFE
ELDORADO SPRINGS
CONTINENTAL
FOREST LAKES
ROLLINSVILLE
SOUTH
TOLLAND
EAST PORTAL
T 1 N
T 1 S
MILES
0
5
TOWNSITES
GEOLOGICAL SITES

Fig. 2--Location of probable early Pleistocene deposits in the Lakewood area that may be glacial; arrows show direction of material transport; dotted traces are trails of radioactive and magnetic ilmenite originating near Caribou; sites, designated by number, are (1) Niwot Ridge, (2) Peneplain, (3) Rainbow Lakes, (4) DeLonde Gulch, (5) Caribou, (6) Eldora Lakes, (7) Ward, (8) Sunset, (9) Sugarloaf, (10) Glacier Lake, (11) Lakewood, (12) Sherwood Flat, (13) Tungsten Mountain, (14) Winiger Ridge, (15) Pactolus, and (16) Thorodin Mountain

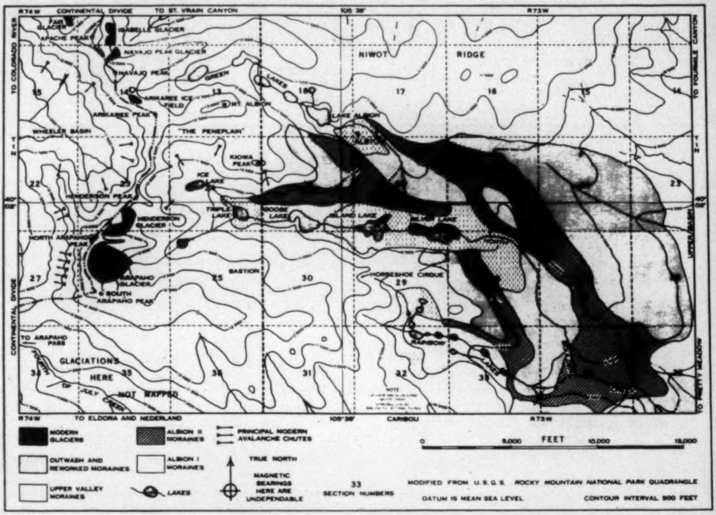
R74W
CONTINENTAL DIVIDE
TO ST. VRAIN CANYON
105°38'
R73W
TO COLORADO RIVER
FAIR GLACIER
ISABELLE GLACIER
APACHE PEAK
NAVAJO PEAK GLACIER
NAVAJO PEAK
GREEN
LAKES
ARIKAREE ICE FIELD
MT. ALBION
ARIKAREE PEAK
WHEELER BASIN
"THE PENEPLAIN"
NIWOT
RIDGE
LAKE ALBION
KIOWA PEAK
ICE LAKE
HENDERSON PEAK
HENDERSON GLACIER
TRIPLE LAKE
GOOSE LAKE
ISLAND LAKE
SILVER LAKE
NORTH ARAPAHO PEAK
ARAPAHO GLACIER
SOUTH ARAPAHO PEAK
BASTION
HORSESHOE CIRQUE
RAINBOW
TO FOURMILE CANYON
TO PRETTY MEADOW
TO ARAPAHO PASS
GLACIATIONS HERE NOT MAPPED
SOUTH FORK OF JULY CREEK
T 1 N
40°02'
15
14
13
18
17
16
22
23
27
25
30
29
34
35
36
31
32
33
R74W
TO ELDORA AND NEDERLAND
105°38'
CARIBOU
R73W
MODERN GLACIERS
ALBION II MORAINES
PRINCIPAL MODERN AVALANCHE CHUTES
OUTWASH AND REWORKED MORAINES
ALBION I MORAINES
TRUE NORTH
MAGNETIC BEARINGS HERE ARE UNDEPENDABLE
UPPER VALLEY MORAINES
LAKES
33 SECTION NUMBERS
0
5,000
FEET
10,000
15,000
MODIFIED FROM U.S.G.S. ROCKY MOUNTAIN NATIONAL PARK QUADRANGLE
DATUM IS MEAN SEA LEVEL
CONTOUR INTERVAL 500 FEET

Fig. 3--Summary map of the principal later Pleistocene glacial features of the Silver Lake and Albion Valleys

Relation of Wisconsin glacial deposits to terrain in the central part of this area (shaded portion of Fig. 2) is shown in Figure 3. Later Pleistocene glaciations in this area have been detailed in several reports [FENNEMAN, 1902; HENDERSON, 1904, 1905, 1906, 1910; IVES, 1935, 1936, 1937, 1939, 1940, 1951, 1953; MOREY, 1927].

The deposits of transported material here to be considered have many features in common. All are composed of Front Range geological materials, and all are deeply weathered, so that the less compact rocks have disintegrated from the combined results of chemical weathering and frost action. In consequence, the deposits are composed of a larger proportion of hard, non-porous rocks, such as Albion monzonite, than are more recent deposits in adjacent areas, from which the less resistant rocks, such as Idaho Springs schist, have not yet been removed by disintegration and erosion.

Because of weathering, erosion, and solifluction, most of the deposits have lost any characteristic morphology which they may once have possessed. Many of the components have been polished, in situ, on their upper surfaces, by windblown sand or windblown snow.

Description of individual deposits

Introduction--The various deposits of transported material will be here summarily outlined, features available in cited literature being mentioned only, and details being included only when they constitute new and pertinent evidence.

Niwot Ridge deposits--Long-continued detailed petrographic studies in the Niwot Ridge area, largely by WAHLSTROM [1947], disclosed that a large number of rocks had been transported more than a mile from their sources, sometimes uphill, and that the mantle rock of Niwot Ridge consisted in large part of transported, rather than of residual, material. Because of the angular nature of the transported material, its motion uphill from the source, the great quantity of material transported, and the total lack of relationship between the direction of transportation and the present and postu-

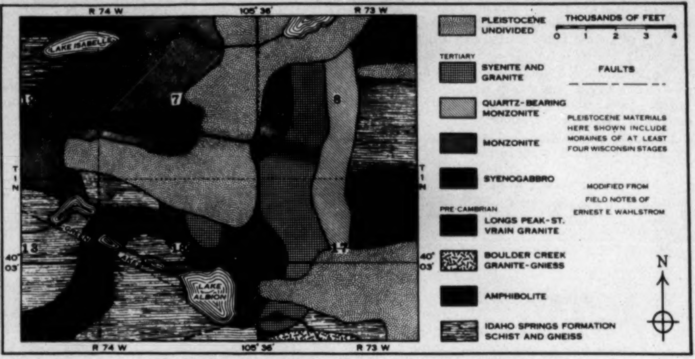
R 74 W
105° 36'
R 73 W
LAKE ISABELLE
7
8
T 1 N
13
18
17
40° 03'
LAKE ALBION
PLEISTOCENE UNDIVIDED
TERTIARY
SYENITE AND GRANITE
QUARTZ-BEARING MONZONITE
MONZONITE
SYENOGABBRO
PRE-CAMBRIAN
LONGS PEAK-ST. VRAIN GRANITE
BOULDER CREEK GRANITE-GNIESS
AMPHIBOLITE
IDAHO SPRINGS FORMATION SCHIST AND GNEISS
THOUSANDS OF FEET
0 1 2 3 4
FAULTS
PLEISTOCENE MATERIALS HERE SHOWN INCLUDE MORAINES OF AT LEAST FOUR WISCONSIN STAGES
MODIFIED FROM FIELD NOTES OF ERNEST E. WAHLSTROM
N

Fig. 4--Geologic map of a part of Niwot Ridge, showing direction and approximate magnitude of material transportation (arrow)

lated past drainage pattern of the area, Wahlstrom attributed this transportation to glacial action. A summary diagram, showing areal geology, direction and magnitude of material transportation, and major terrain features, comprises Figure 4. This area constitutes 1---1 in Figure 2.

The peneplain sites--Evidence that the supposedly unglaciated peneplain between Albion and Kiowa Peaks (Fig. 2, site 2) was glaciated in several places was found by the writer in 1933, and augmented by later field investigations [IVES, 1933, 1934]. General appearance of this peneplain, as viewed from the south, is shown in Figure 5. This area contains site 2 of Figure 2. The evidence here consists of a striated surface at the south edge of the peneplain, a group of decayed roches moutonees (under Ⓐ in Fig. 5), and a small polished and striated area, badly decayed, uncovered in an excavation east of Albion Peak. Considerable rock transportation, from west to east, has also taken place here, as on Niwot Ridge. This evidence shows plainly that at least a portion of the peneplain was glaciated. The type and extent of the glaciation is not so clearly shown. At Ⓐ (Fig. 5), the motion was to the southeast, toward the present Silver Lake Valley, whereas east of Albion Peak the trend of the striae was approximately east and west.

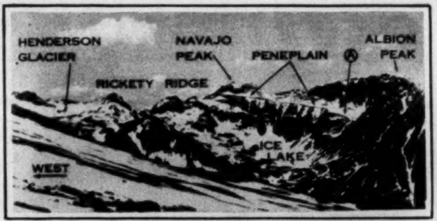
HENDERSON GLACIER
NAVAJO PEAK
PENEPLAIN
Ⓐ
ALBION PEAK
RICKETY RIDGE
ICE LAKE
WEST

Fig. 5--View of a part of the peneplain between Albion and Kiowa Peaks, from the south; place names here agree with those of Figure 3; site of important glacial evidence is indicated by Ⓐ

The Caribou deposits--Many of the supposedly glacial deposits in the Caribou area were found by miners and prospectors about 1900, and further studied by large numbers of students from the University of Colorado from about 1910 on. These consist of a large number of piles and masses of unstratified and weathered material, of Front Range origin, but almost invariably

east of their probable source. These resemble the deposits from continental glaciers, rather than those from alpine glaciers, and all are of small areal extent and depth. There is no convincing evidence that all of these deposits (numbers 3 and 5, Fig. 2) are of the same age. From the Caribou Flats, a trail of magnetic "black sands" can be traced with a magnetometer as far as Lakewood and Nederland. A part of this trail is along extant drainages, and another part goes over a low divide and eastward into DeLonde Gulch. Loss of a film cache due to fogging on long storage at Caribou led to the discovery that many of the ores there were radioactive, and a subsequent check with a Geiger counter showed that the "black sand" trails were also the approximate centers of zones of elevated Geiger count. (Counts exceeding five times regional background were noted in a few places.)

Eldora Lakes deposits--Morainal deposits at Eldora Lakes (site 6, Fig. 2) consist of some materials much like those at Caribou; and other masses of transported material similar to that atop Niwot Ridge. A small amount of material, at a comparable level, on a small bench on the north side of Fourth of July Gulch (near site 5, Fig. 2) is quite probably an extension of the Eldora Lakes deposits. This area is currently under investigation by P. G. Worcester of the University of Colorado.

Peripheral deposits--Located close to the terminal moraines of the later Pleistocene glaciers, but physically distinct from them, are a large number of small deposits of suspected morainal material, all of small volume and deeply weathered, and all of Front Range origin. Many of the identifiable components are most commonly found in place at sites farther west. These deposits are sites 4, 7, 10, 11, and 12 of Figure 2.

Tungsten Mountain--South and east of Nederland, on the northwest slope of Tungsten Mountain, and in its vicinity, is a series of boulder and gravel deposits believed to represent not only a terminal moraine, but also outwash from it. This material, of Front Range origin, is much older and more deeply weathered and dissected than the nearby moraines of the Eldora Valley glacier system of later Pleistocene age. A discussion of this deposit (site 13, Fig. 2) is contained in ATWOOD and ATWOOD [1938] and a more thorough description is given by LOVERING [1940]. Field checking in this area discloses the substantial correctness of the cited evidence.

Outwash deposits--Several miles east of the moraines of the later Pleistocene glaciers, occupying relatively flat areas atop divides between the present streams of the area, are thin sheets of coarse gravel, with occasional boulders. These closely resemble the glacial outwash of the northern plains, and are transported material, but the mode of transportation is not indicated by the field evidence. Major sites are numbers 8, 9, 14, 15, and 16 of Figure 2. One of these (No. 14) is quite obviously an eastward outlier of the Tungsten Mountain deposit (No. 13); the others are almost identical in appearance and arrangement.

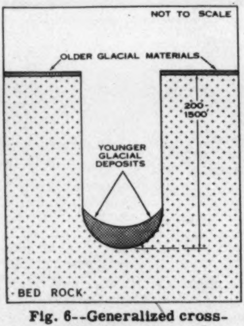

Fig. 6--Generalized cross-section of a valley and upland area, showing relation of older to younger glacial materials

Terrain relations

When these deposits are mapped on a topographic base, several relations become apparent. Deposits at high levels are all above the later Pleistocene glaciated areas, and most are on the supposedly unglaciated peneplain. A cross section of a valley and upland area, showing these relations, constitutes Figure 6.

Generalized relations of peneplain surface, later Pleistocene glacial structures, and older glacial and transported materials, are shown in longitudinal section of a similar area in Figure 7.

From the location and distribution of these deposits, it is apparent that all of them were laid down upon a surface approximating that of the so-called peneplains, and that their location bears little relation to the present drainage pattern.

Conclusions from the evidence

From the evidence here cited, it appears that materials were transported eastward for a distance of several miles from the present Continental Divide area, and deposited on upland surfaces.

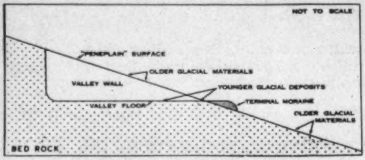

Fig. 7--Longitudinal section of a valley and upland area, showing generalized relation of later glacial structures, peneplain surface, and older deposits of glacial and transported materials

In several areas, notably near Albion Peak (Fig. 2, site 2) and Tungsten Mountain (Fig. 2, site 13), the glacial nature of the deposits is practically certain. In consequence, it can be stated with confidence that parts, at least, of the peneplains were glaciated.

Because of the great similarity of all of the deposits to each other, and to deposits left by continental glaciers, attribution of all of them to glacial action seems not unreasonable. This assumption is supported by the lack of relation of the directions of transportation to present-day drainage patterns and gradients.

In consequence, the most probable explanation of these deposits is that they were transported and deposited by glacial ice, probably of the ice-cap type, prior to the dissection of the uplands.

Reconstruction of grades in this area, prior to the later Pleistocene glaciations, indicates that the summit of the ancient Front Range was slightly west of the present Continental Divide.

From the obviously incomplete evidence now remaining, an ice cap atop the Front Range during one or more glacial phases of the earlier Pleistocene is postulated, with a center approximately over Wheeler Basin, and an eastern termination about eight miles east of the present Continental Divide.

Evidence from the Colorado Headwaters area (Fig. 1, site 2) is not incompatible with this assumption. North of the area here considered, there is a gap in the evidence, east of Estes Park; then similar evidence resumes on both flanks of the Front Range, so that a similar ice cap can be postulated for that area, with less confidence, however, because less evidence has been found.

It is entirely possible, but not conclusively demonstrated by evidence now known, that the entire summit of the Front Range, and of parts of the Never-Summer and Medicine Bow Mountains, were covered by an ice cap early in the Pleistocene. Until more, and more conclusive, evidence is found, however, this ice cap must be considered a working hypothesis, and not a proven fact.

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THE DISPOSAL OF INDUSTRIAL EFFLUENT BY WOODS IRRIGATION

John R. Mather

Abstract--A method for the disposal of industrially polluted effluent -- by woods irrigation -- is described, and the results of hydrologic investigations during the first year of operation are evaluated. It was found that the spraying of 400 to 600 inches depth of water on the woods area did not harm the vegetation, clog the soil, or result in saturation of the area. A maximum of about 50 million gallons of water were removed from the selected 180-acre disposal area weekly by ground-water discharge and evapotranspiration. Analyses of well water from the woods area showed no indication of pollution as a result of the disposal operation.

Introduction

The processes of production in most industries result in the creation of varying amounts of polluted effluent. Because of recent legislation, the disposal of this effluent is becoming a primary problem to many industries. Stream disposal of polluted waste water is no longer permissible in many regions while, in others, local authorities are putting increased pressure on industries for stream-pollution abatement. In order to implement local groups working toward stream-pollution control the Federal Government in 1948 drew up the National Pollution Control Act (P. L. 845, 80th Congress). This act, although recognizing the primary rights of the individual states to pursue their own stream-pollution policies, sets up the means whereby the Federal Government can give both financial and technical aid to strengthen state pollution-abatement policies and to help resolve interstate pollution problems. A number of interstate compacts have already been entered into for the control of pollution in streams which flow through more than one state. Examples of such interstate organizations are the Ohio River Valley Water Sanitation Commission, the New England Interstate Water-Pollution Control Compact, and the Interstate Commission on the Delaware River Basin. Thus, recent legislative developments pose a threat to the very existence of many industries, for if they are unable to dispose of their polluted effluent by presently recognized methods they must either move to other regions where stream disposal is permitted or go out of business. Considerable effort has been expended by industries to develop and improve methods of effluent disposal.

At the present time the most conventional methods of waste-water disposal are the use of standard or high-rate bio-filters, the ponding of effluent so that it may seep into the ground or be discharged into streams after putrefactive decomposition has occurred, and the use of filters and chemicals which will aid in the collection of the dissolved and suspended solids and, thus, render the effluent safe for stream disposal. Though recent advances have been made through chemistry [ANONYMOUS, 1951ab] toward a solution to the waste-water disposal problem, expense and the varying nature of the polluted effluent prevent the widespread use of these disposal methods at present.

The Seabrook Farms Co., Seabrook, New Jersey, a leader in the growing and quick-freezing of vegetables, uses from five to ten million gallons of water a day in the processing of its produce. The traditional method of handling food-plant effluent is by stream disposal or lagoon detention. However, because of the nature of the streams near the Seabrook processing plant and the large volume of the effluent, these methods of disposal are impractical. A careful survey of other methods of waste-water disposal was begun in 1949 but it soon showed that no entirely satisfactory method existed because of expense or the probable lack of continued success. In the spring of 1950 C. W. Thornthwaite of the Johns Hopkins University, realizing the possibility of returning the effluent to the land by irrigation, designed an irrigation system to handle the volume of the Seabrook effluent. Basically the system consists of spraying the effluent through giant rotating nozzles into a woodland. The effluent will be removed from the wooded area by evapotranspiration and percolation to the ground-water table. The solids in the effluent will filter out in the vegetation litter and upper soil layers and be removed rapidly by organic decomposition. The solids added to the area by filtering from the effluent will be far less in amount than those added by the forest itself in the form of leaves and twigs and should be decomposed more rapidly than the forest products. The disposal system has an additional advantage in that it is relatively inexpensive to install and yearly operating costs are low.

Irrigation systems to dispose of water on either cultivated or uncultivated land have been used before by other industries and by state groups. In most cases the volume of the water to be applied was less than a tenth of the Seabrook volume and the results achieved were far from satisfactory. Thus, the Seabrook installation is of considerable interest for it is one of the first times that an irrigation system has been used successfully in the disposal of such large volumes of effluent.

This paper will describe the Seabrook installation and discuss the results of investigations carried out by the author during the first year's operation, which ran from May 8 to December 15, 1950. Because of the success of the first year's program, woods-disposal operations were undertaken on an even larger scale in the spring of 1951. Results of the second and third years' operations which will not be discussed in detail in the present paper have shown that the system is far more satisfactory than could have been anticipated from the results of preliminary investigations.

The U. S. Geological Survey, recognizing the research potentialities of such an undertaking, established a cooperative research program on ground-water movement in the area at the beginning of 1951.

Selection of site for waste-water disposal

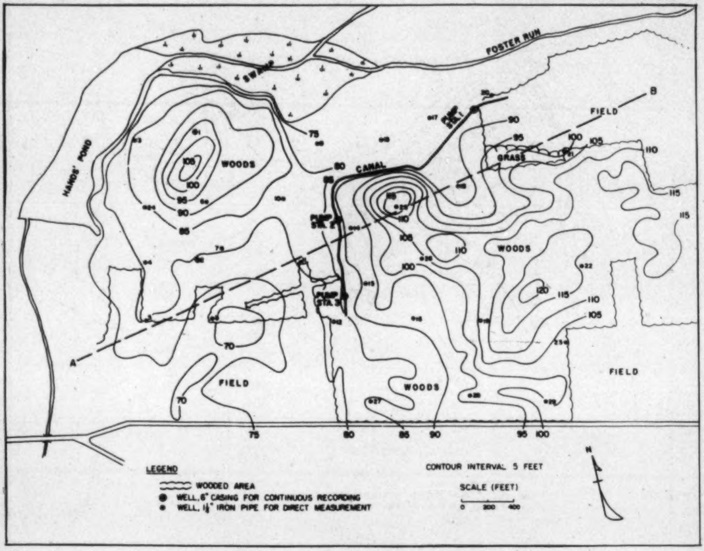
Seabrook Farms owns about 20,000 acres of land in south-central New Jersey around its packing plant. Although most of this is cultivated, some wooded tracts still remain. In selecting the site for the irrigation-disposal system a number of field infiltration tests were made in different areas. In general, it was found that forest soils had a much higher water absorbing and holding capacity than did the cultivated land. In one area two inches of water sprayed onto a cultivated field in a day resulted in saturation and surface runoff. Four hundred feet away in a wooded area with soil of the same physical composition, over 150 inches of water was sprayed onto the area over a ten-day period without noticeably saturating it.

Similar results have been found by other investigators. HURSH [1944] showed that the noncapillary storage capacity of an undisturbed forest area is almost three times that of a cleared and eroded area. This higher storage capacity results in less overland runoff during storms. DREIBELBIS and POST [1941] noted this same result in a study of four watersheds, one predominantly woodland, one pasture, and the other two cultivated. With an annual precipitation of 35.9 inches, the woodland and pasture watersheds had 0.11 and 0.60 inches of runoff respectively, while the cultivated watersheds gave 6.09 and 6.35 inches of runoff. The authors concluded that the runoff must be affected by the amount of litter present. In a study of the different water-holding capacities of cultivated and forest soils, HUBERTY [1944] concluded that it was the compaction resulting from cultivation, especially during periods of high moisture content, which caused the lowered permeability. Those soils which had the widest range of particle sizes seemed to suffer the greatest reduction in permeability due to cultivation.

Because of the low infiltration rates of cultivated fields, Thornthwaite decided to spread the bulk of the Seabrook effluent in a forested area. However, the application of large amounts of water daily to an area is not a simple undertaking. Irrigation, especially on a large scale, is a scientific venture and will only be successful when it is controlled by continuous scientific study and investigation. There are, for instance, a number of factors which must be considered in determining the suitability and size of an area for waste disposal by irrigation. Chief among these are the topography of the disposal area, the character of the soil profile, the nature of the vegetation, the depth to the ground-water table, and the quality of the surface and ground water in the area.

On the basis of investigations of these and other factors, a 180-acre wooded tract located about two miles from the Seabrook plant was selected for waste-disposal operations. Some of the physical characteristics of the selected area will be discussed below. Careful study of the physical nature of the disposal area is important, for the design of the disposal system to be employed in each individual case can only be determined from an evaluation of such studies.

Topography of the disposal area--The surface topography of the area selected for waste disposal is shown in Figure 1. The surface elevation varies from 70 ft in the southwestern part of the area to over 120 ft in the southeastern part. The relation of the several high areas to the east of the canal and the one to the west with the surrounding depressions results in a markedly rolling surface configuration. Because of this, the selected area is not too desirable for large-scale irrigation operations.


FOSTER RUN
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110
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LEGEND
WOODED AREA
WELL, 6" CASING FOR CONTINUOUS RECORDING
WELL, 1½" IRON PIPE FOR DIRECT MEASUREMENT
CONTOUR INTERVAL 5 FEET
SCALE (FEET)
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Fig. 1--Topographic map of area selected for industrial waste disposal project, Seabrook, New Jersey

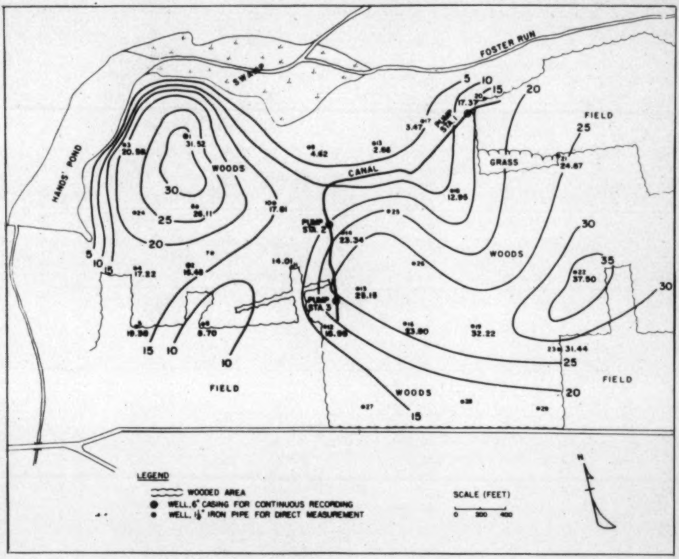
Character and amount of vegetation--Preliminary vegetation studies in the disposal tract carried out during the 1950 season [DAVIS, BROWN and JACKSON, 1951] have been extended during each of the succeeding years of operation. A yearly survey of the effect of the water on the forest vegetation will permit the planning of spraying operations to curb or hasten vegetation changes as may be desired.

The trees of the wooded area, averaging 300 to 400 per acre, are primarily white and black oaks. The ground-cover vegetation consists of flowering dogwood (Cornus florida) and blueberry (Vaccinium spp.) which are well distributed through the woods and mountain laurel (Kalmia latifolia) which is concentrated most densely in the southwestern section of the area.

Character of the soil profile--The coastal plain region around Seabrook is broken by scattered lenses of impermeable clay. Fifty soil borings were made in the disposal area and clay layers were found in 22 of them. Most of these layers appear to be small and restricted in areal extent. As such, they do not materially reduce the permeability of the soil.

Mechanical analyses by means of the Bouyoucos method using 100 grams of air-dried soil and ten minutes dispersion in a Waring blender have been made on a number of soil samples from the disposal area. The average results for the surface layer are as follows: sand 79 per cent; silt 11 per cent; clay 10 per cent.

Depth to ground-water table--Twenty-nine observation wells were installed in the area so that regular measurements of the depth to the water table as well as chemical and biological analyses of water samples could be made. Ground-water table observations were made in the selected disposal tract on May 1, 1950 (Fig. 2) before any effluent had been sprayed into the region. The depth to water in the area at that time was found to vary from about two to 35 ft with the average depth to water being about 25 ft.


FOSTER RUN
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LEGEND
WOODED AREA
● WELL, 6" CASING FOR CONTINUOUS RECORDING
• WELL, 1½" IRON PIPE FOR DIRECT MEASUREMENT
SCALE (FEET)
0 200 400
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Fig. 2--Depth to ground water table in feet, May 1, 1950, in disposal area

Quality of surface and ground water--Chemical and biological analyses performed on groundwater samples from the observation wells in the forested area revealed a very striking fact. Several of the wells sampled before any polluted effluent was sprayed into the forest area showed moderate biological oxygen demands and reduced dissolved oxygen concentrations. As a result, the water would be termed unpotable according to health standards. More surprising than the discovery of this natural pollution of the ground water in the forest was the fact that as soon as the effluent from the processing plant was applied to the ground, the biological oxygen demand fell rapidly and the dissolved oxygen concentration rose. The water in the wells became potable. Spraying of the effluent through the air evidently saturates it with oxygen, while its percolation through the leaf mold, organic remains, and upper soil layers filters and purifies it so that it rapidly becomes potable.

Woods-irrigation disposal installation

A woods-irrigation disposal system, to operate most efficiently, must be adapted to the physical characteristics of the disposal area and the nature of the effluent. The effluent at Seabrook Farms is screened after it leaves the processing plant to remove most of the suspended solids. It then flows by gravity in an open canal over 9000 feet long to the selected disposal area shown in Figure 1.

The open canal is a most important part of the Seabrook disposal system for it delivers the effluent to the disposal area without any pumping costs, allows a good percentage of the remaining suspended solids in the effluent to settle out so that they will not be sprayed into the woods, and aids in the loss of water by means of seepage and evaporation while in transit. The flow of water from the plant to the disposal area is measured daily at several places in the system. A Venturi meter is located in the pipe line just before the water enters the open canal while a Parshall flume has been placed in the canal about one mile from the processing plant. Pressure gages at each of the pumps and at every nozzle position permit the computing of the amount of water sprayed into the woods. Thus a careful record of the amount of water flow in all parts of the system is maintained. The results of these measurements of effluent flow have been averaged by months in Table 1. From these data it is possible to calculate the average daily water loss from the canal. Water losses by evaporation and seepage amount to over a million gallons a day at the start of the season and fall to about 300,000 gallons a day toward the end of the year due to the sealing of the soil with the organic material in the effluent and the rise of the water table beneath the canal. Before the start of the second year the layer of organic material was scraped from the sides and bottom of the canal. During the second year similar high seepage losses were experienced for the first two months. Again, a marked reduction in losses occurred toward the end of the year.

Table 1--Average daily disposition of effluent from processing plant during 1950 (in thousands of gallons)

Month	From processing plant	In canal, one mile from plant	Sprayed into woods	Lost in transit in canal
May	3500	----	2300	1200
June	6100	5600	4900	1200
July	3900	3600	3200	700
August	5100	4700	4500	600
September	6000	5700	5600	400
October	5000	4700	4600	400
November	3500	3300	3200	300

The effluent is pumped from the canal at three pumping stations, and sent through eight- and six-inch portable steel irrigation pipe into the woods. Giant nozzles, nine along each of the irrigation lines, spray the effluent into the woods. Although movement of the lines and nozzles is to be avoided as much as possible to reduce operating costs, some movement was necessary during the first year to insure continued efficient operation.

The pumps which take the water out of the open canal are each capable of pumping a million and a half gallons a day at pressures of 90 lb/in^2. Three of the nine nozzles operate at a time from each of the irrigation lines. Each nozzle will spray about 21,000 gallons of water per hour into the woods at a pressure of 60 lb/in^2. Since the spray from each nozzle covers about an acre, this results in the application of 0.8 of an inch of artificial rainfall per hour per nozzle. Eight million gallons daily is the equivalent of approximately 300 acre inches of rainfall. Each nozzle is operated for eight hours a day, applying approximately 6.4 inches of rainfall.

The importance of water-table measurements in disposal operations has been mentioned previously. In order that the fluctuations in the water table resulting from the irrigation operations could be followed and used in planning future operations, weekly measurements were made at each of the 29 observation wells located in the area (see Fig. 1). The number of observation wells was increased to 35 during the first year of operation in order to obtain a more complete picture of the position of the water table. At the beginning of the 1951 season eight more wells were added, as the disposal area was enlarged slightly in anticipation of increased disposal operations.

Hydrologic investigations during the first year's operation

Distribution of sprayed effluent in disposal area--The flow of waste water from the processing plant to the disposal area is quite variable depending on the day and season of year. During 1950 the daily flow varied from zero on days without plant operation to a maximum of 10.1 million gallons during the pea harvest and a maximum of 11.9 million gallons during the spinach harvest. The total flow of industrial effluent from the processing plant during 1950 amounted to 941 million gallons. Furthermore, the 33 inches of rainfall during the operating season added about 187 million gallons of water to the amount of industrial effluent. All of this water had to be disposed of in the woods area.

Water pumped from the canal in the woods is sent through the irrigation lines to the nozzles. It was necessary to relocate the lines and nozzles from time to time during the season because of the lack of experience in evaluating the ability of various parts of the forest area to absorb large quantities of water. As a result of an intensive study of the water-absorbing capacities of the area, permanent nozzles locations were selected by September, 1950. Three months of satisfactory operation during 1950, nine months of operation in 1951, and the first four months of operation (up to the time of this writing) in 1952 at these locations show that no further relocation will probably be necessary.

Due to variation in operational procedure, and to the shifting of the line and nozzle positions during 1950, the amount of effluent sprayed into the forest region varies considerably from one section to another. Figure 3 shows the depth of water applied by the nozzles to the woods area.

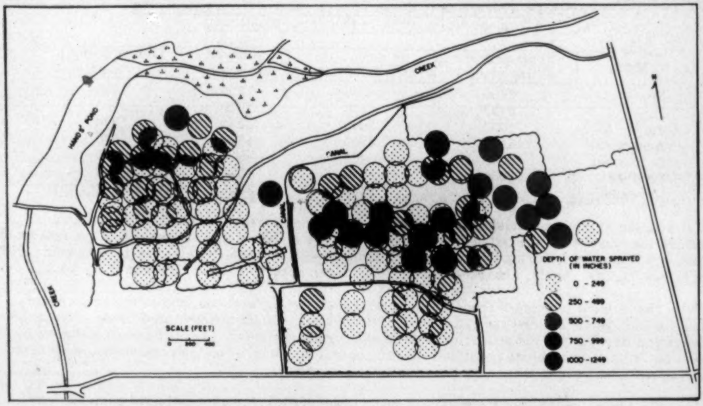

Fig. 3--Distribution of sprayed industrial effluent in disposal area, Seabrook, New Jersey, May-December, 1950

In those regions not reached by the spray, no water was applied. The maximum depth of water, 1,183 inches, was applied to a region north of well 15 near the center of the disposal area. This high concentration resulted from the overlap of the spray from several nozzles. The average depth of application by a nozzle was 500 to 600 inches during the 1950 operating season. Higher applications were found in regions of spray overlap.

Preliminary analysis of the data for 1951 shows that the total flow of effluent from the processing plant during the second year of operation amounted to about 1.2 billion gallons. Figure 4 shows the depth of water applied by the nozzles to the woods area. A comparison of Figures 3 and 4 reveal several significant features. Although the amount of effluent to be disposed of in 1951 was about 25 percent greater than in the previous year, the experience gained during the 1950 season resulted in the spreading of water on fewer areas in the woods. Nozzle positions were unchanged during the year. The amount of water applied at each nozzle location was much more uniform; for example, 56 of the 62 areas being sprayed received from 500 to 749 inches depth of water. The average application was about the same as in the previous year, approximately 600 inches. The distribution of sprayed effluent during 1951 was much more satisfactory and efficient than during 1950.

Figures 3 and 4 were obtained by assuming that the spray from each nozzle covered just one acre during each revolution. This is not exactly true, for as the pressures at the spray nozzles varied from 65 to 55 lb/in^2 with increasing distance along the irrigation lines, the area covered by the spray varied from just over to just under one acre. Knowing the time of operation of each nozzle and the rate of water application, the depth of water sprayed could be computed. In regions of overlapping spray, the depths of water applied by all contributing nozzles were summed.

The distribution of the sprayed industrial effluent shown on Figures 3 and 4 is of importance in any further analysis of the effect of the disposal operation on plants, animals, soil, and the water table. Such analyses are in progress at the present time.

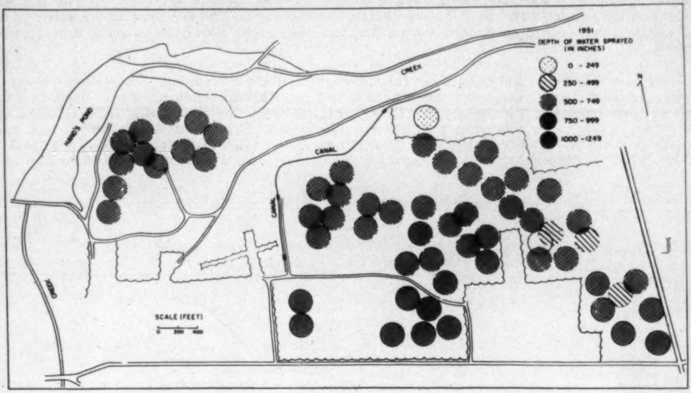
1951
DEPTH OF WATER SPRAYED (IN INCHES)
0 - 249
250 - 499
500 - 749
750 - 999
1000 - 1249
N
CREEK
HAND'S POND
CANAL
CANAL
CREEK
SCALE (FEET)
0 200 400

Fig. 4--Distribution of sprayed industrial effluent in disposal area, Seabrook, New Jersey, May-December, 1951

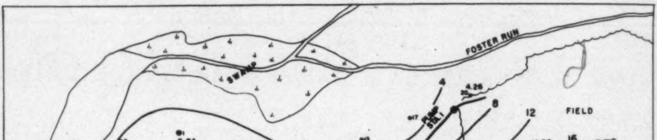
FOSTER RUN
SWAMP
HANDS' POND
WOODS
CANAL
FIELD
GRASS
PUMP STA. 1
PUMP STA. 2
PUMP STA. 3
WOODS
FIELD
WOODS
FIELD
4
8
12
16
20
4.26
5.13
6.64
9.64
14.06
10.69
5.18
12.48
11.08
4.32
7.32
13.63
22.72
17.07
4.81
8.70
12.50
13.24
16.28
LEGEND
WOODED AREA
WELL, 6" CASING FOR CONTINUOUS RECORDING
WELL, 1½" IRON PIPE FOR DIRECT MEASUREMENT
SCALE (FEET)
0 200 400
N

Fig. 5--Rise in level of ground-water table, in feet, in disposal area, May 1-December 11, 1950, as a result of spraying operations

Changes in the ground-water table--On the basis of the weekly measurements of the 29 observation wells, it was seen that the application of large amounts of water could result in great local changes in the water table during short periods of time. The response of the water table to changes in the watering regime at the surface was quite rapid, usually showing up in less than a week.

Two maps (Fig. 5 and 6) have been prepared to show the change in the depth of the water table during the first year of operation at Seabrook. The maximum change in the depth to the water table from May 1 to December 11, 1950 (Fig. 5) during the period of effluent spraying operations is seen to be somewhat over 22 feet. The average change during the same period was just over ten feet. Figure 6 shows the change in the water table depth from May 1, 1950 to April 30, 1951, when disposal operations began for the second year. Essentially no woods irrigation occured from December 15, 1950 to April 30, 1951. The small amount of water used in the processing plant during this period was stored in the canal but, because of the high rate of water loss from it by seepage, no sprinkler irrigation was necessary. On April 30, 1951, the water table in the southeastern section of the disposal area was still about nine feet above its level at the beginning of operations in 1950. Recovery of the water table in the rest of the area to pre-disposal levels was almost complete, the average change for the entire woods area being a rise of just over two feet.

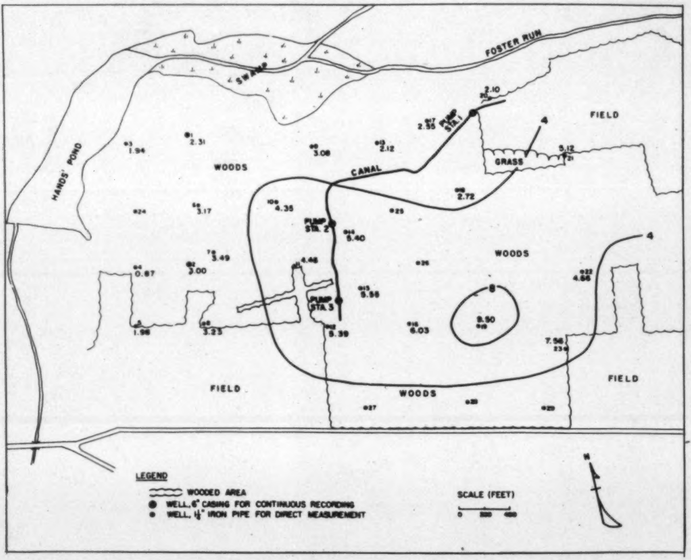
FOSTER RUN
SWAMP
HANDS' POND
WOODS
CANAL
PUMP STA. 1
PUMP STA. 2
PUMP STA. 3
GRASS
FIELD
WOODS
FIELD
FIELD
WOODS
4
4
8
2.10
2.55
2.31
1.94
3.08
2.12
2.72
5.12
3.17
4.35
5.40
3.49
4.46
0.87
3.00
5.56
9.50
4.66
1.96
3.23
5.39
6.03
7.56
LEGEND
WOODED AREA
WELL, 6" CASING FOR CONTINUOUS RECORDING
WELL, 1½" IRON PIPE FOR DIRECT MEASUREMENT
SCALE (FEET)
0 200 400
N

Fig. 6--Rise in level of ground-water table, in feet, in disposal area, May 1, 1950 to April 30, 1951

The return of the ground-water table to the levels measured before the start of the disposal operations is not necessary for the successful continuation of the disposal system as long as a sufficiently large unsaturated soil layer is available to insure vegetation growth. Studies have shown that ground-water discharge is slight until a steep ground-water table gradient has been

established. As the slope of the water table increases, the ground-water discharge from the area becomes greater. Figure 6 shows that at the start of the 1951 disposal season ground-water table gradients were slightly greater than at the same time in 1950. This means that the initial rate of underground runoff will be somewhat greater at the start of 1951. It does not mean that less water can be sprayed onto the area, for it is not only the available water-storage space in the soil which determines the utility of an area for spraying operations but also the maximum rate at which ground-water discharge can occur.

A comparison of Figures 3 and 5 shows that the greatest changes in the water table, in the eastern part of the disposal area, correspond well to the region of heaviest application of water by the spray nozzles. Agreement is even more striking if one considers weekly values.

Water-table changes may also be shown by means of a profile across the disposal area. Figure 7 shows such a profile running northeastward across the woods area along line A-B on Figure 1. The depths to the water table at four different times during the year are included. As a result of over-irrigation in the western part of the area, a small lake formed when the water table reached the surface by the end of June. By August 7, continued irrigation had brought the water table to the surface in the dale in the eastern part of the area and resulted in the formation of a small spring which had a very low rate of flow. The water from this spring was potable.

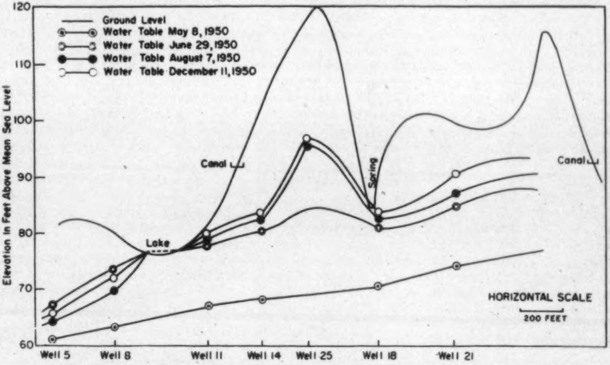

Fig. 7--Surface and ground-water table profiles across industrial waste disposal area during water-spreading operations, 1950

Water balance in disposal area--The success of the woods-irrigation disposal scheme depends on the ability of the woods area to absorb and get rid of the daily sprayed effluent. If more water is put on the area than leaves by percolation through the ground or evapotranspiration, water will be stored in the ground and the water table will rise. As the water table rises, its slope becomes steeper and the rate of movement of water through the ground increases. However, if this increased ground-water outflow is still not adequate to balance the total daily volume of sprayed effluent, further rises in the ground-water table will result. Swamps or overland runoff will occur if the water table reaches the surface.

To compute the amount of water which the disposal area could lose by ground-water discharge and evapotranspiration each week, a hydrologic balance for the area was set up. Since water is added to the disposal area only by the irrigation sprays and by precipitation and water is lost only by evapotranspiration and ground-water discharge (essentially no surface runoff from the area occurred), the difference between these sets of terms must equal the change in the amount of water stored in the soil. Water storage in this case includes not only the ground-water storage but also the water temporarily in the unsaturated zone in transit to the ground-water table and the

water stored in surface ponds and pools. For convenience, the storage may be divided, therefore, into two parts -- the measured storage as shown by changes in the ground-water wells and the unmeasured storage in ponds and in the unsaturated zone. Solving the relation for the ground-water discharge and the unmeasured storage, the two terms which cannot be readily measured, one obtains

$$R \pm \Delta S_u = D + P - (E \pm \Delta S_m)$$

where R = ground-water discharge, ΔS_u = unmeasured change in water storage, D = water added by disposal operations, P = precipitation, E = evapotranspiration, and ΔS_m = measured change in underground storage of water. A rise in the water table results in a positive value of ΔS_m while a fall in the water table gives a negative ΔS_m value.

Certain assumptions must be made in order to evaluate the terms in the right-hand side of the above relation. D and P can be measured by the proper gages. E may be determined for a woods area by means of THORNTHWAITE's [1948] empirical expression relating evapotranspiration to temperature and day length. ΔS_m may be evaluated from the ground-water table observations and an estimate of the porosity of the soil.

Table 2 shows the results of the weekly evaluations of the terms in the water-balance relation. Column (2) was obtained from records of nozzle pressures and times of operations for each day of the operating year. The precipitation over the area was determined by averaging the results obtained from three rain gages located near the borders of the wooded area. Column (5) was obtained from Thornthwaite's potential evapotranspiration formula. The values of evapotranspiration have been adjusted to account for the fact that evapotranspiration did not occur at the potential rate over the entire woods area throughout the whole summer. Any errors in the determination of evapotranspiration which may result, however, are unimportant in view of the large volume of water added to the area and the relatively insignificant role of evapotranspiration in the overall water balance of the area. Column 6 was obtained by determining the total net change in the ground-water table over the area and by assuming a figure for the porosity of the soil of 0.3. Column (8) results from a combination of the values in the other columns. In physical terms the values in Column (8) are the sums of the ground-water discharge, the volume of water stored in ponds and pools in the area, the water stored temporarily in the soil above the ground-water table, and the surface runoff. The volume of water stored in ponds and pools in the area was small and relatively constant after the first five or six weeks, while the surface runoff was negligible throughout the year. The amount of water in temporary storage above the water table was probably variable during the year depending on the amount of water spreading and precipitation which occurred. Thus, the values in Column (8) from the beginning of July through the end of the year should approximate the ground-water discharge except for changes in temporary water storage in the unsaturated zone. As long as the amount of water added to the area was fairly constant, this latter term would also remain almost constant from week to week. Early season variations in the values in Column (8) probably resulted in large part from variations in the temporary storage of water in the unsaturated zone and in the storage of water in the pond shown in the profile of Figure 7.

From May 22 to July 23 approximately 320 million gallons of water were added to the disposal area. In that same period the amount of water stored in the soil as shown by the changes in the ground-water table was about 160 million or approximately half of the water added. The ground-water discharge and unmeasured storage amounted to about 130 million gallons. During the period from September 11 to October 29, again approximately 320 million gallons of water were added to the forest area. In this period only about 12 million gallons of water were added to the ground-water table as storage in the area while the ground-water discharge and the unmeasured storage amounted to about 295 million gallons. Although certain small differences in the amount of unmeasured storage in the area might exist between these two periods, it is clear that a marked increase in the volume of ground-water discharge was the most significant difference between the periods. Because of the rise in the water table and the increased water-table gradients in the area, a large increase in the rate of ground-water discharge results.

To give a better view of the changes, some of the values in Table 2 are presented in graphical form in Figure 8. The curve of water added by spreading and precipitation shows two maxima, one during late June and the other early in September when over 70 million gallons of water per week were added to the 180-acre disposal area. During the rest of the year, weekly amounts of water added to the area were less than 55 million gallons. The total amount of water lost by evapotranspiration and stored in the soil was quite high at the start of disposal operations. As

Table 2--Water balance sheet for disposal area, Seabrook, New Jersey (all values in millions of gallons)

Period (1)	Water spread D (2)	Precipitation P (3)	D + P (4)	Evapotranspiration E (5)	Change in ground-water storage in area ΔS_m (6)	$E \pm \Delta S_m$ (7)	(4 - 7) (8)
1950							
May 22-28	26.0	3.2	29.2	2.5	17.9	20.4	8.8
May 29-June 4	17.0	8.8	25.8	2.7	20.9	23.6	2.2
June 5-11	20.5	2.3	22.8	3.5	18.6	22.1	0.7
June 12-18	38.7	4.5	43.2	2.8	40.1	42.9	0.3
June 19-25	58.7	11.6	70.3	3.6	46.9	50.5	19.8
June 26-July 2	41.4	0	41.4	3.8	5.1	8.9	32.5
July 3-9	16.6	5.9	22.5	3.8	-1.3	2.5	20.0
July 10-16	27.9	9.3	37.2	3.9	8.6	12.5	24.7
July 17-23	27.1	3.0	30.1	3.5	0.9	4.4	25.7
July 24-30	31.7	1.7	33.4	3.6	8.2	11.8	21.6
July 31-Aug. 6	42.4	5.1	47.5	3.5	7.7	11.2	36.3
Aug. 7-13	33.6	2.0	35.6	3.2	1.2	4.4	31.2
Aug. 14-20	27.1	1.8	28.9	3.3	1.1	4.4	24.5
Aug. 21-27	37.2	0	37.2	3.0	5.1	8.1	29.1
Aug. 28-Sep. 3	46.6	4.7	51.3	4.0	8.2	12.2	39.1
Sep. 4-10	46.8	32.3	79.1	2.7	25.0	27.7	51.4
Sep. 11-17	39.6	14.3	53.9	4.0	7.3	11.3	42.6
Sep. 18-24	47.5	8.5	56.0	1.8	7.9	9.7	46.3
Sep. 25-Oct. 1	43.7	0.5	44.2	1.6	0.8	2.4	41.8
Oct. 2-8	38.7	0.1	38.8	1.7	-1.5	0.2	38.6
Oct. 9-15	46.2	3.9	50.1	1.5	5.8	7.3	42.8
Oct. 16-22	44.2	6.3	50.5	1.5	8.4	9.9	40.6
Oct. 23-29	20.6	6.7	27.3	1.1	-16.0	-14.9	42.2
Oct. 30-Nov. 5	31.7	2.4	34.1	1.6	-4.2	-2.6	36.7
Nov. 6-12	36.4	0.1	36.5	0.7	-1.7	-1.0	37.5
Nov. 13-19	23.2	0	23.2	0.6	-5.3	-4.7	27.9
Nov. 20-26	8.2	35.8	44.0	0.7	7.2	7.9	36.1
Nov. 27-Dec. 3	9.9	1.2	11.1	0.6	-6.2	-5.6	16.7
Dec. 4-10	6.8	7.9	14.7	0.6	-12.9	-12.3	27.0
Dec. 11-17	5.5	2.7	8.2	0	-14.2	-14.2	22.4
Dec. 18-25	0	0	0	0	-16.3	-16.3	16.3
1950-51							
Dec. 26-Jan.2	0	2.4	2.4	0	-17.9	17.9	20.3
1951							
Jan. 3-8	0	3.0	3.0	0.4	-9.7	-9.3	12.3

the water-table slopes increased, seepage through the ground became greater and the amount of underground storage increased less rapidly. By late October, the water table in the disposal area began to recede because the addition of water to the area by spraying was less than the combined ground-water discharge and evapotranspiration. The total volume of water stored in the soil decreased, resulting in negative ΔS_m values. Ground-water discharge and unmeasured storage, the difference between the water added and lost, was low at the start of the season as a result of the low water-table gradients. As the water table rose the ground-water discharge increased to a maximum of just over 50 million gallons in early September. Through September and October weekly ground-water discharge averaged about 45 million gallons. It is certain that had more water been added to the disposal area during these months the ground-water discharge could have been increased slightly. A weekly discharge of about 50 million gallons appears to be a reasonable maximum value for the area which was in use during 1950.

Water analyses--Daily chemical and biological analyses of the water from three of the 29 observation wells were made during the disposal season. No sign of increasing pollution was noticed in any of these wells as a result of the effluent spraying. From the analyses of the water samples it is clear that the woods area was a most efficient disposal plant, rapidly converting polluted industrial effluent into potable water by means of percolation through the ground. Similar results have been found during the 1951 and 1952 disposal seasons.

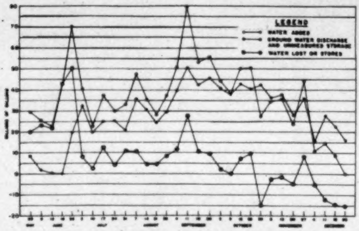

Fig. 8--Weekly water balance sheet for industrial waste disposal area, Seabrook, New Jersey, May - December, 1950; water added includes precipitation and effluent spraying while water lost includes evapotranspiration and changes in the amount of water stored in the soil

Additional disposal-area problems

The disposal of polluted water by woods irrigation seems to solve a major industrial problem. However, for the long-term successful operation of a woods-disposal area, continuing scientific investigations must be carried on. Chief among the problems demanding continuous study are the nature of the vegetational changes resulting from the high rates of water spreading, soil erosion in the disposal area, and the effect of the chemical composition of the water on soil permeability.

Vegetation changes--Little information exchanges that will occur as a result of the spreading operations. After almost three years of disposal operations at Seabrook, some changes can be listed but it is certain that they represent only a percentage of the total which will occur over a period of years. Because of the physical force with which the sprayed water strikes the vegetation, branches and leaves have been knocked off nearby trees and shrubs. Blueberries and huckleberries, common in the woods area, were thinned out in the sprayed areas by the action of the water. Small trees having most or all of their leaves knocked off by the water were killed. Larger trees whose crowns were above the spray were not seriously affected in general. Certain species, however, reacted unfavorably to the water. In the Seabrook area, chestnut oak did not seem to be able to survive the spraying operation although all the other oak species present are still flourishing under the higher amounts of water.

Once the thinning out of the blueberries and huckleberries had occurred, their place was taken in the Seabrook woods by weeds such as pigweed, fireweed, horseweed, and poke. During the second and third years of operations these weeds grew luxuriantly in the sprayed areas where the normal ground cover was not present. The weeds reached heights of ten to 12 ft with stalks over two inches in diameter. They provided a far better ground cover than was present on the a area during the first year's operation. Since the weeds flourish under the high soil moisture conditions, they should always provide an adequate cover in the sprayed areas. Three years of observations have shown no damage to vegetation which would seriously affect the forest litter and reduce the infiltration capacity of the soil.

Soil erosion--Because of the amounts and rates of application of water in the disposal area and the thinning out of the ground cover during the first year, soil erosion could become a problem of major significance if care is not taken in planning operations.

ELLISON [1945] has pointed out the effect of splash erosion both to the surface configuration and to the infiltration rates. The presence of a leaf litter or ground cover eliminates splash erosion almost entirely. In the Seabrook area, during the week or two required for the annual weeds to cover the areas thinned by the spraying operations, it was necessary to regulate the amount and rate of irrigation application to control erosion. Greater experience will permit a more efficient, increased use of the disposal area in the future without fear of erosion.

Effect of effluent on soil permeability--Because of the presence of dissolved solids in the effluent, especially sodium, some doubt was expressed whether the high rates of infiltration noticed during the first year would continue. HARRIS [1931] has shown that on calcareous soils the soil permeability decreases exponentially as the sodium content increases. The Seabrook effluent contains sodium from time to time during the year. The high rates of leaching during the rest of the year, however, probably eliminate much of the danger of a reduction in permeability as a result of sodium cation exchange. Three years' observation of the rates of accumulation and breakdown of the dissolved and suspended solids in the effluent indicates that probably no serious blocking of the soil pores will be noticed as a result of the spraying operations.

Conclusions and future possibilities

The disposal of industrially polluted effluent by means of woods irrigation described above provides a radically different solution to a complex problem of growing importance to industry. Conclusions based on three seasons of disposal operation, although tentative, are extremely promising. The spreading of 400 to 600 inches of water onto forest soil at Seabrook, New Jersey, during an eight-month period, while causing a rise in the water table did not seriously harm the vegetation, clog the soil, or result in swamps or a completely saturated soil. In fact, as a result of the vegetational changes accompanying the spraying operations the disposal area appeared to be better covered the second and third years than before operations began. Recovery of the ground-water table to pre-disposal operation levels was nearly complete during the four-month winter period without disposal operations. The vegetation and soil of the disposal area act as a most efficient filter, for on the basis of well analyses it was found that no pollution of the ground-water table had occurred as a result of the spraying of the polluted effluent.

About 50 million gallons of water per week were removed from the original disposal area by ground-water discharge and evapotranspiration. Relocation of the nozzles in more favorable areas in 1950 resulted in a slight increase in this amount of ground-water discharge and permitted high rates of effluent spraying to be maintained without damage to the area and without further relocation of the nozzles.

Based on these observations, tentative conclusions are that waste disposal by woods irrigation at Seabrook is entirely satisfactory. There is every indication that as long as operations are maintained within the limits dictated by the physical characteristics of the area, satisfactory results will be achieved. Disposal of waste water by woods irrigation is a relatively new and unproven disposal scheme but it gives promise of offering a cheap, efficient method of waste disposal. Although only tried so far for the disposal of freezing- and canning-plant effluent, the scheme might be useful in the disposal of the non-toxic, organically-polluted effluent of other industries. However, woods irrigation is a scientific undertaking which requires careful initial study and planning as well as continued reinvestigation if it is to be a successful long-term venture.

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SOIL PRIMING IN RELATION TO SNOW SURVEYS AND FLOOD REGULATION

M. W. Nelson, H. G. Wilm, and R. A. Work

Abstract--In earlier analyses of techniques for water forecasting in the Columbia River Basin, both water yields and flood discharges were found to be highly correlated with the water content of snow as determined by snow surveys, and with the amount of precipitation which occurred during the spring. Studies described in this paper demonstrate the additional correlation obtained by including data on autumn precipitation in the forecast analyses. Recorded for the autumn preceding each spring flood, these data express the degree of "soil priming" in the Basin--the extent to which autumn deficits in soil moisture are replenished by precipitation before the snow-pack accumulates each winter. Data on this variable were included in a linear multiple regression equation, with snow water content and spring precipitation as the other independent variables. As compared to previous analyses, the inclusion of the soil-priming variable made a 40 pct improvement in the standard error of the forecasts, made on April 1 of each year. Smaller improvements in precision were observed for later forecasts, made on May 1 and May 15.

Introduction--This paper is a sequel to an earlier one [NELSON, WILM, and WORK, 1951]. A factor termed "soil priming" is computed and used in forecast equations which adds still greater accuracy to the long-range forecasts based mainly on snow data of peak flow and volumes of the Columbia River. This sequel does not describe any change of the relationship between short-period volume flows and peaks, but rather describes a method for increasing accuracy of the volumetric forecasts, which in turn will improve accuracy in prediction of peak flows.

The soil-priming factor--Watershed soils have a definite or limited water-holding capacity, usually expressed as a percentage of oven-dry weight or volume of the soil. Above this wetness, all water added to the soil profile will percolate down to the ground water or be lost in surface runoff. If the soil moisture is below this percentage, any water added to the soil must first fill this soil-moisture reservoir before deep percolation or excessive runoff will occur. Precipitation on watersheds in the fall of the year thus influences runoff at a later date. If greater-than-average fall precipitation occurs, the soil will normally be well primed. Therefore, little or none of the snow melt may be required to bring the soil profile to its maximum moisture-holding capacity. Precipitation below average during the fall period may leave the soil moisture deficient. This deficiency must then be supplied from the melting snow and the anticipated water yield from the watershed is reduced. In the case of the Columbia River, it was found that rainfall during August, September, and October greatly influenced the following spring's streamflow.

The quantitative determination of the soil-priming factor is computed by averaging the departure from normal of precipitation at stations on the sub-drainages of the Columbia River for August, September, and October, and then multiplying that average by the per cent contribution the sub-drainage makes at the forecast point (see Table 1). When these values are computed for all the sub-drainages and added algebraically, the sum provides a forecasting variable.

Other factors included in the analysis--Aside from the soil-priming factor, three other variables were employed in analyses leading toward forecasts of water yields and flood peaks:

(1) The weighted average water equivalent of snow, computed in a manner similar to that employed for the soil-priming factor. Forty-three selected snow courses in Columbia Basin provide these data (see Table 1).

(2) The spring-precipitation departure for the month of April, to be used in the May 1 forecast.

(3) A second spring-precipitation variable, expressing the departure of precipitation from normal for April and the first half of May.

In Table 2 are shown the data for all forecasting variables, computed for the Columbia River Basin above The Dalles, Oregon, for the years 1937-50, inclusive.

Forecasting procedures--The techniques to be employed in these analyses correspond in general form to those discussed in the earlier paper by these authors. Early in April, the first

Table 1--Information for determining water equivalent of snow and precipitation departures for forecasting the flow of the Columbia River near The Dalles, Oregon

Rivers	Weighting factor, pct of contribution near The Dalles, Ore. April - June	Snow water variable, snow courses averaged	Precipitation departure, stations added algebraically for average departures
Columbia at Birchbank, British Columbia	47.8	Canoe River, B. C. Field, B. C. Glacier, B. C. Sinclair Pass, B. C. Red Mountain, Montana	Fortine, Montana Revelstoke, B. C.
Clark Fork at Heron, Montana	13.7	Chessman Reservoir Freezeout Summit Hoodoo Creek Lookout Pass Marias Pass Mosquito Ridge Nezperce Pass Packers Meadow Slide Rock Summit Stuart Mountain No. 1 Upper Ten Mile Creek	Belton, Montana Columbia Falls, Montana Kalispell, Montana Polson, Montana
Clearwater at Spalding, Idaho	11.4	Forty-nine Meadows Kit Carson Pasture Nezperce Pass Packers Meadow Savage Pass	Pierce, Idaho
Salmon at Whitebird, Idaho	7.9	Deadwood Summit Big Creek Summit Mill Creek Williams Creek Moose Creek	Salmon, Idaho Challis, Idaho
Snake at Weiser, Idaho	8.0	Black Rock Valley View Trinity Big Creek Summit	Moran, Wyoming McCall, Idaho
Spokane at Post Falls, Idaho	4.1	Forty-nine Meadows Huckleberry Mountain Kellogg Peak Lookout Pass Roland and Sunset Medicine Creek Mosquito Ridge	Avery, Idaho Roland, Idaho
Yakima at Parker, Washington	2.5	Blowett Pass Bumping Lake Fog Basin Lake Cle Elum	Bumping Lake, Washington Lake Kachess, Washington Rimrock, Washington
Okanogan at Tonasket, Washington	2.1	Aberdeen Lake McCulloch Mission Creek Summerland Reservoirs Trout Creek Harts Pass	Oroville, Washington Summerland, B. C. Osprey Lake, B. C.

Table 2--Summary of weighted snow water, precipitation departures, and April-June flow volumes, Columbia River

Year	Snow water final weighted average	Precipitation departure, final weighted average			Flow volumes
		Aug-Oct.[a]	April	April-May 15	
		inch	inch	inch	10^6 ac ft
1937	13.7	-2.91	+1.04	+0.40	42.8
1938	19.3	-1.05	+0.10	-0.10	68.5
1939	16.6	-0.88	-0.27	-0.38	50.5
1940	13.2	-1.51	+0.54	+0.54	48.1
1941	10.3	+0.37	-0.62	-0.18	38.1
1942	11.6	+3.36	-0.10	+0.64	51.4
1943	22.8	-1.61	+0.42	+0.21	70.8
1944	11.0	-1.15	+0.19	-0.11	33.8
1945	13.8	-0.64	+0.47	+0.46	50.1
1946	20.8	+0.18	+0.26	+0.05	71.7
1947	20.4	+1.15	+0.14	-0.01	66.5
1948	18.4	+2.89	+1.29	+1.95	89.5
1949	24.6	-1.17	-0.54	-0.71	67.6
1950	24.4	+0.19	+0.39	+0.06	72.2
1951[b]	22.4	+1.34	-0.27	+0.11	72.9

[a] This variable is for the preceding fall.

[b] 1951 not included in the forecasting equations, but used to test equations for preceding years.

prediction of volume for April through June and peak flow of Columbia River is made, based upon the weighted snow water equivalent of April 1 qualified by the preceding fall's precipitation departures from normal. These forecasts are sufficiently accurate to allow water users and reservoir operators to make preliminary plans for water regulation. Thereafter, on May 1 and May 16, more exact forecasts can be made, again using April 1 snow surveys qualified both by antecedent and spring precipitation departures. The forecasts become increasingly accurate as the season proceeds. By statistical means, each forecast of peak and volume can be accompanied by estimates of its error and the probable limits within which the actual yield or flood discharge is likely to fall. The regression equations for forecasting water yields are shown in Table 3.

Table 3--Regression equations for estimating water yields, Columbia River

Forecast date	Equation	Coefficient of determination	Coefficient of correlation	Variance of estimate	Standard error of estimate[a]	Equation
April 1	$14.239 + 2.627X_1 + 3.850X_2$	0.788	+0.88	53.618	7.32	(1)
May 1	$12.389 + 2.608X_1 + 3.888X_2 + 9.2733X_3$	0.892	+0.94	27.211	5.22	(2)
May 15	$7.402 + 2.879X_1 + 1.943X_2 + 11.083X_4$	0.935	+0.97	16.361	4.04	(3)

[a] Millions of acre feet.

In each case, X_1 is the weighted average water equivalent of snow as measured approximately April 1 of each year; X_2 is the "soil-priming variable"; X_3 is the antecedent precipitation departure for April; and X_4 is the corresponding departure for April and half of May. As compared with the results obtained without the use of autumn precipitation departures, these equations are more precise in their estimates of water yields, especially for the first spring forecasts. Without the soil-priming variable, the coefficient of correlation of the equation for the April 1 forecast was +0.79; this is increased to +0.88. Similarly, the coefficients for the May 1 forecast were +0.86 without the soil-priming variable, and +0.94 with it. As a result, the standard error of the April 1 forecast is reduced approximately 40 pct by the inclusion of the soil-priming factor.

To compute the weighted snow water equivalent, the snow courses within each sub-watershed of the Columbia River as shown in Table 1 are averaged; that average is then multiplied by the percentage contribution of that sub-drainage at the forecast point (in this case, The Dalles, Oregon). The sum of all the weighted snow water equivalents for each contributing drainage constitutes the snow-water variable. This figure is combined in the forecast of April 1 with an antecedent precipitation departure variable computed in the same manner but using precipitation stations rather than snow courses. For the forecasts of May 1 and 16, a third variable is computed by use of the weighted average precipitation departures for April and one-half of May, using the same stations as in the computation of antecedent precipitation departure. These departures and the weighted average snow water are used together to obtain a revised estimate of total volume to be expected during the period April through June.

For the April forecast of peak discharges, these variables of antecedent precipitation and water equivalent of snow are first correlated with the flow volume for April through June in each year of record. In predicting a new year, the April-June volume, estimated from the above two variables, is inserted into Eq. (4) (see Table 4) expressing the relation of peak to April-June flow volume. This gives a preliminary estimate of peak discharge as of April 1. Later, on May 1, the volume is re-forecast, correcting the April 1 forecast in view of precipitation departures from normal during April, and then a residual volume forecast for May-June is determined by subtracting actual April flow from the revised April-June forecast. This reduced volume is inserted into (5) based on the relation of peak discharge to May-June volume, and the forecast peak is determined. A corresponding procedure is followed for the May 16 forecast of peak flow by employing (6). Just as in the case of estimated flow volumes, each succeeding forecast is more accurate than the one before; the coefficient of correlation rose from +0.88 on April 1 to +0.97 by May 15.

Table 4--Equations for estimating peak discharges from estimated yields, Columbia River at The Dalles

Forecast date	Equation, E_q =	Coefficient of determination r^2	Coefficient of correlation r	Equation
April 1	$-82.889 + 10.558E_v{}^a$	0.772	+0.88	(4)
May 1	$-102.91 + 13.370E'_v{}^b$	0.886	+0.94	(5)
May 15	$-60.142 + 15.196E''_v{}^c$	0.926	+0.96	(6)

[a] E_v = Forecasted April-June volume.

[b] E'_v = Forecasted April-June volume, less observed April volume.

[c] E''_v = Forecasted April-June volume, less observed volume in April and first half of May, of forecast year.

Illustrations of forecast procedure--In order to demonstrate the procedures discussed above for the forecasting of flow volumes and flood peaks, it is desirable to make actual forecasts for a year that is not included in the regression analyses. Accordingly, the following discussions will present analyses of data on water yields, peak discharges, water equivalent of snow, and precipitation departures through 1950. Then forecasts are made for 1951 and compared with the actual April-June volumes and flood discharges that occurred in 1951. The observed data are also plotted on Figures 1, 2, and 3.

At the time of the forecast of April 1, 1951, the weighted snow-course average was 22.4 inches (see Table 5). The precipitation departure for the preceding period August-October 1950 was +1.34 inches. Applying these figures to Eq. (1) in Table 3 or to the regression lines shown in Figure 4 provides an April-June forecast of 78.2 million ac ft for the Columbia River at The Dalles. This forecast necessarily assumes that both temperature and precipitation over the Basin through April-June will be approximately average, since dependable long-range forecasts of either temperature or precipitation are not available. As compared to the actual water yield for April-June, 1951, the forecast yield is higher by 5.3 million ac ft, about 7.3 pct. As shown by the indicated magnitude of t, a deviation this large could be expected by chance about every other year.

As soon as the estimate of 78.2 million ac ft is available, this figure can be applied to the regression of peak discharges on volumes to obtain a forecast of the 1951 peak discharge. Using Figure 1 or Eq. (4)

$$E_q = -82.889 + (10.558)(78.2) = 743 \text{ thousand cfs}$$

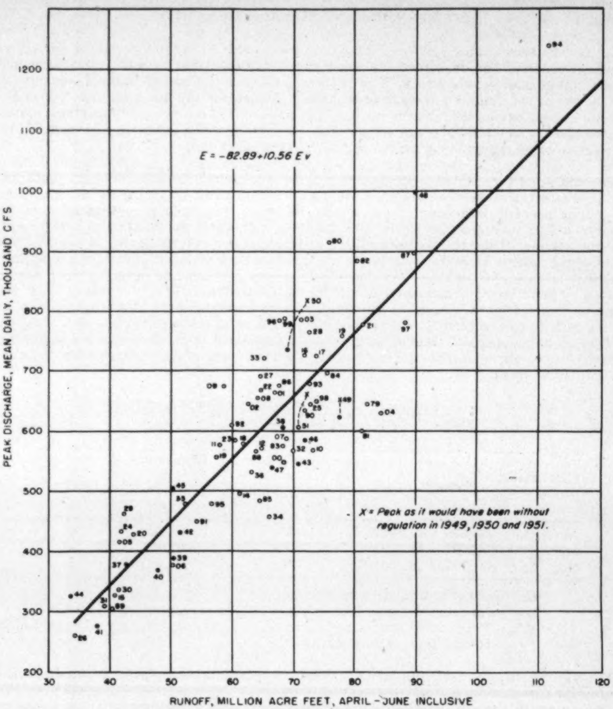

Fig. 1--Relation of peak discharge to April-June volume

Table 5--Runoff data for 1951[a]

Period	Flow volumes	Changes in reservoir content	Flow volume adjusted for reservoir change
1951	ac ft	ac ft	ac ft
April	15,009,000	+811,000	55,820,000
May 1-15	10,814,000	+471,000	11,285,000
May 16-31	17,883,000	+471,000	18,354,000
June	27,321,000	+114,000	27,435,000
May 16-June 30	45,203,000	+585,000	45,788,000
May 1-June 30	56,017,000	+1,056,000	57,073,000
Apr.-June	71,027,000	+1,867,000	72,894,000

Average weighted snow water as of April 1st	22.4 inches
Average weighted precipitation departure as of May 1st	-0.27 inch
Average weighted precipitation departure as of May 16th	+0.11 inch
Flow data as follows: Actual peak (regulated)	601,700 cfs
Computed peak (unregulated)[b]	652,000 cfs

[a] Preliminary only.

[b] Supplied by Corps of Engineers, U. S. Army.

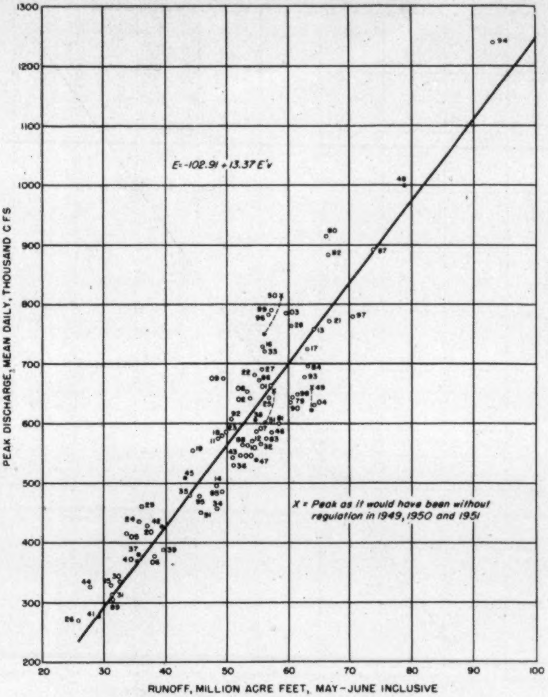

Fig. 2--Relation of peak discharge to May-June volume

Table 6--Forecasts of peak discharges, Columbia River at The Dalles, 1951 (thousands of cubic feet per second)

Forecast date	Forecast	Deviation forecast from computed	Standard error	t[a]	p[b]
April 1	743	+91	122	0.75	0.5
May 1	668	+16	101	0.16	0.9
May 15	679	+27	88	0.31	0.8

Computed peak without regulation, 652,000 cfs

[a] Students t = deviation divided by standard error.

[b] p = probability that observed difference will be exceeded in other trials.

As shown in Table 6, the forecast exceeded the computed peak without regulation by 91,000 cfs. As in the case of the April 1 water-yield forecast, a deviation this large could be expected about once in two years.

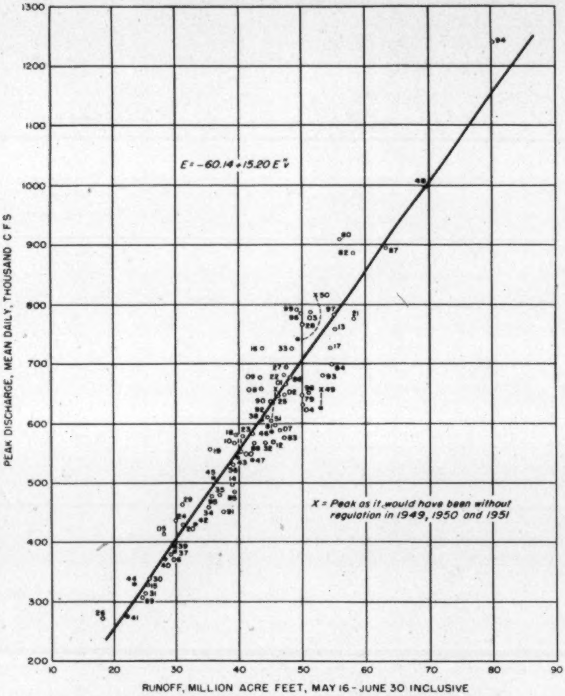

Fig. 3--Relation of peak discharge to May 16-June 30 volume

Table 7--Forecasts of discharge volumes for April through June, 1951, Columbia River (millions of acre feet)

Forecast date	Forecast	Deviation forecast from observed	Standard error	t[a]	p[b]
April 1	78.2	+5.3	8.09	0.66	0.5
May 1	73.5	+0.6	5.92	0.10	0.9
May 15	75.7	+2.8	4.82	0.58	0.6

Observed volume, 72,900,000 ac ft

[a] Students t = deviation divided by standard error.

[b] p = probability that observed difference will be exceeded in other trials.

Soon after May 1, 1951, data were available on the departure of April precipitation from normal. Then this figure as well as the April 1 snow water equivalent and the preceding fall precipitation departure can be inserted into Figure 5 or Eq. (2) to supply an improved estimate of the total volume of water to be expected for the period April-June, 1951

$$E_V = 12.389 + 2.608(22.4) + 3.888(+1.34) + 9.2733(-0.27) = 73.5 \text{ million ac ft}$$

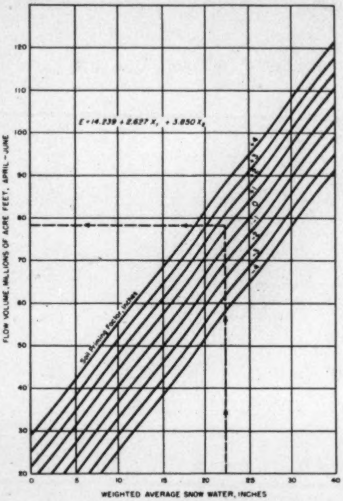

Fig. 4--Relation of flow volume to snow-water content and soil priming factor April 1

With this revised volume figure available, the first step toward a forecast of peak discharge is to subtract the April flow volume (corrected for reservoir storage) from the estimate

$$73.5 - 15.8 = 57.7 \text{ million ac ft}$$

still expected to flow down the river between May 1 and June 30. This estimate can then be inserted into (5) or read from Figure 2 to give a new peak estimate as of May 1

$$E_q' = -102.91 + (13.370)(57.7) = 668 \text{ thousand cfs}$$

To refine the May first forecast of peak further, it would be desirable to refer to May 1 snow surveys. Not as many May 1 snow surveys have been conducted as those of April 1 nor, in many cases, are the records as extended in years. It seems certain that, with passing years, snow surveys on May 1, May 15, and even June 1 will be found essential for close river regulation.

The peak forecasts of April 1, May 1, and May 16 are for river flow with a minimum of regulation. There are now reservoirs on the Columbia capable of storing enough water to materially reduce the peak flow at The Dalles. The amount of reduction possible and planned must be considered in determining any final forecast of the probable flood discharge at The Dalles, and of the resultant correlated harbor stages at Portland and Vancouver.

By the time of the May 16 forecast, still more data are available on the continued departure of precipitation from normal and on the volume of water that has already passed The Dalles.

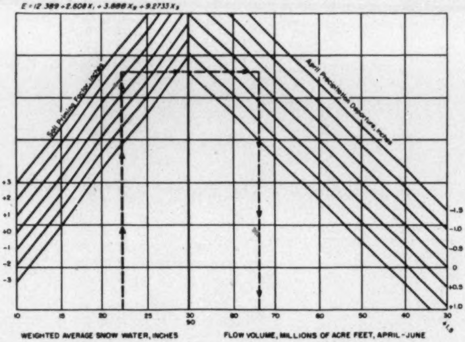

Fig. 5--Relation of flow volume to snow-water content, soil-priming factor, and precipitation May 1

These can be used to supply still later and more refined forecasts of total April-June volume and of the expected peak discharge.

Using Figure 6 or Eq. (3), an estimate of April-June volume is obtained as follows

$$E_V'' = 7.402 + 2.879(22.4) + 1.943(+1.34) + 11.083(+0.11) = 75.7 \text{ million ac ft}$$

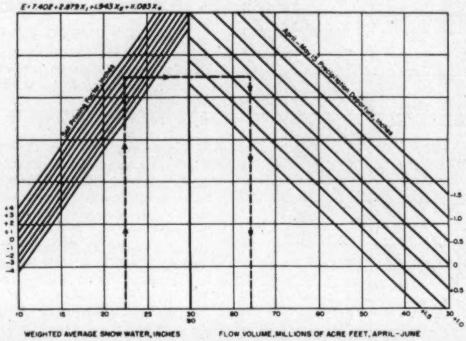

Fig. 6--Relation of flow volume to snow water content, soil-priming factor, and precipitation departure through May 15

This forecast deviates from the observed volume by only 2.8 million ac ft, about 3.8 pct. You will notice the substantial increases in precision in the successive forecasts, as indicated by the standard errors in Table 7.

The discharge of the Columbia River at The Dalles from April 1 to May 15 was 27.1 million ac ft. This is deducted from the revised total three-month estimate of 75.7 million ac ft. When this quantity is inserted into Figure 3 or Eq. (6), the peak discharge is estimated to be

$$E_q'' = -60.142 + (15.196)(48.6) = 679 \text{ thousand cfs}$$

The observed peak in 1951 was 602,000 cfs, which was less than the amount forecast because of up-river reservoir regulation. The forecast peak deviated from that which would have occurred without reservoir regulation by only 27,000 cfs. As compared to the standard error, this deviation is exceptionally small.

Reference

NELSON, M. W., H. G. WILM, and R. A. WORK, Use of snow surveys in planning regulation of Columbia River floods, Proc. 19th An. Mtg., Western Snow Conf., pp. 1-29, 1951.

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SEDIMENT PROBLEMS IN LAKE MEAD AND DOWNSTREAM ON THE COLORADO RIVER

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Abstract--This paper gives an outline of the effects on the regimen of the river, only in part foreseen, which were produced by the construction of Hoover Dam on the great sediment-carrying Colorado. The effects fall in two categories: (1) The many phenomena that occur in an arid region when a great lake, more than a hundred miles long and in places more than 600 feet deep, storing almost two and one-half average years' yield of the watershed, is created within a few years. The phenomena have to do with the distribution within the volume of the reservoir of the great incoming sediment load, with the travel of the incoming water through the stored volume, of the stratification of the lake due to temperature and salinity, and, finally, to the seismic effect of the great accumulated weight. (2) The phenomena occurring on the river above, and particularly below, the dam when the river bed adjusted to a sediment-laden stream is suddenly forced to accommodate a flow of clear water, and when the yearly fluctuations of flow from flood to drouth are changed to an almost steady discharge.

The sedimentation survey of Lake Mead, formed by Hoover Dam, undertaken in 1947-1950, yielded, for the first time, precise data on the travel and deposition of sediment, on the circulation of the water within the lake, and on the general subsidence of the Earth's crust caused by the weight of the water. The paper gives an outline of the main results of the survey pending the publication of a complete report. The paper also gives an outline of the 20 years' accumulation of data on the regimen of the Colorado River below Hoover Dam, the changes which have taken place because of the construction of the dam, and the physical work which has been executed and is still in progress so as to help the river to adjust itself to the new conditions.

Available sediment space in Lake Mead--When Hoover Dam was being designed, it was clear to the engineers associated with this unprecedented work that the enormous quantities of sediment which would enter the reservoir after the completion of the dam would be deposited there and in some way affect the operations of the project. Some knowledge was available as to the magnitude of the sediment load in that continuous suspended-load sampling had been in progress at the Geological Survey's gaging station at Grand Canyon since 1926. On the basis of records up to, say, 1934, or the time when the dam was under construction, the average inflow of suspended load into the lake might be estimated at some 224,000,000 tons per year. The space which this weight of sediment would occupy in the reservoir was unknown, but, on the basis of unit weight determined by FORTIER and BLANEY [1928] of approximately 85 lb/ft^3 and 15 pct added for bed load, the average volume loss caused by sediment accumulation would be approximately 139,000 ac ft per year.

How and where this sediment load would be deposited within the confines of the reservoir were not only questions to which there were no answers, they were also questions which had never been considered at the time Hoover Dam was built. Disturbing evidence was existent at the time at Elephant Butte Reservoir in New Mexico, but the evidence was not known outside a very small and local circle. The designers of Hoover Dam, therefore, did what all dam designers had done before them, and what at the time was considered as a valid procedure. They allowed a sediment storage volume at the bottom of the reservoir below the elevation of the sills of the lowest outlet gates. At Hoover Dam, this elevation is 895 ft, and the volume below it at the time the dam was built was 3,200,000 ac ft.

In February, 1935, the tunnel outlet gates of Hoover Dam were closed and the reservoir began to fill, and the questions of sediment deposition within the reservoir were largely forgotten. Some short-lived interest was aroused in September and October of 1935 when muddy water was suddenly discharged through the outlet pipes, as described by GROVER and HOWARD [1938].

Early density-current observations--At about the same time, some seemingly entirely different phenomena were observed in the laboratories of California Institute of Technology where an investigator was experimenting to see what would happen if a stream of water, purposely made slightly heavier than ordinary water by the addition of colored salts, was introduced into clear water. It was found that, under certain circumstances, such a stream would travel for long distances (on the model scale) through the body of clear water without greatly losing its identity. Pictures were made of the behavior, simulating a muddy river when it entered a model reservoir, and again it was found that, under certain circumstances, such a stream would travel through the entire length of the reservoir until it was dissipated at the face of the dam. These phenomena were of considerable theoretical interest, and, to study them further, the National Research Council in 1937 established a Committee on Density Currents, under the chairmanship of Herbert N. Eaton, and with a rather wide membership. In the course of the early discussions in that Committee, it was realized that the muddy discharge at Hoover Dam, later described by Grover and Howard, might indicate that a density current of muddy water might have traveled the entire length of Lake Mead. It was also brought to light that similar phenomena had been observed at Elephant Butte Dam. Thus, there was evidence that density currents existed not only in the laboratory, but even in reservoirs as large as Lake Mead. For that reason a subcommittee, under my direction, was formed by the Density Current Committee, with the task assigned to trace the possible flow of density currents in Lake Mead. The report of that subcommittee was completed in 1941, and has since been reprinted by the U. S. Bureau of Reclamation entitled Lake Mead Density Currents Investigations, 1937-1940, 3 volumes.

It was disclosed that at certain times of year great portions or perhaps the entire inflow into Lake Mead traveled along the bottom of the reservoir, following the old river bed, without greatly mixing with the standing water in the reservoir, and finally becoming dissipated at the face of the dam, very much along the lines indicated by the model experiment. It was also disclosed that substantial volumes of sediment, reaching a depth substantially in excess of 100 feet, had accumulated immediately upstream from the dam. Since the lake is clear, this sediment could have been transported the long distance from the head of the reservoir only by means of density currents.

Organization of the sedimentation survey--Even though the volume of sediment thus deposited near the dam was considerable, it was only a small portion of the estimated volume of the total sediment inflow. The question arose as to the deposition of the remainder of the sediment load. Only a thorough sedimentation survey could furnish the answer to this question representing a major effort requiring substantial funds and personnel. Neither funds nor personnel were available during the war years; hence, it was not until 1947 that the question of a sedimentation survey of Lake Mead was again being given serious consideration.

Thanks to the whole-hearted cooperation of several Government agencies, including the Navy, the Geological Survey, the Coast and Geodetic Survey, and the Bureau of Reclamation, this unprecedented sedimentation survey was undertaken and completed late in 1950. The final report on the survey was scheduled for publication early in 1953. This paper gives some of the more important results.

The volume of sediment--From the time the reservoir first began to fill until the time the survey was done, a total weight of approximately 2,004,000,000 tons of sediment entered the reservoir, occupying a space of 1,425,000 ac ft, and corresponding roughly to an average unit weight of 64.8 lb/ft^3. The greatest depth of sediment deposit was found at the upper reaches of the reservoir, far above the sediment pocket provided when the dam was designed, and thus largely within the useful operating volume of the lake. The maximum depth was found to be 270 ft. Proceeding toward the dam, the depth of sediment deposit decreased, but along the original river channel deposits 45 to 160 ft deep were found almost the entire distance to the dam, as shown in Figure 1. At the dam itself the sediment deposit had a thickness of 106 ft. Smaller accumulations of sediment were found in the Virgin Basin at the mouth of the Virgin River (see Fig. 2). Only 42 pct of the total sediment volume has been deposited within the designated sediment pocket below the lowest outlet gates.

Disregarding the relatively small amount, 5,500 ac ft, deposited above the elevation of the permanent spillway crest, 1205.4 ft, the total volume of deposits is distributed approximately as shown in Table 1.

The sediment accumulation was determined by the use of echo-sounding equipment operated from boats. Two types of echo-sounding devices were used. One, a low-frequency set manufactured by Bludworth-Marine, Inc., which, in the western part of the reservoir, was able to penetrate the sediment, showing both the top of the accumulated sediment and the underlying topography of the original reservoir floor. The other was a high-frequency set manufactured by Bendix Aviation, which showed only the top of the sediment, but with more precise definition. Sounding courses running essentially parallel to each other across the wide portions of the reservoir were spaced 200 to 300 yards, controls being obtained by sextant and transit observations to and from

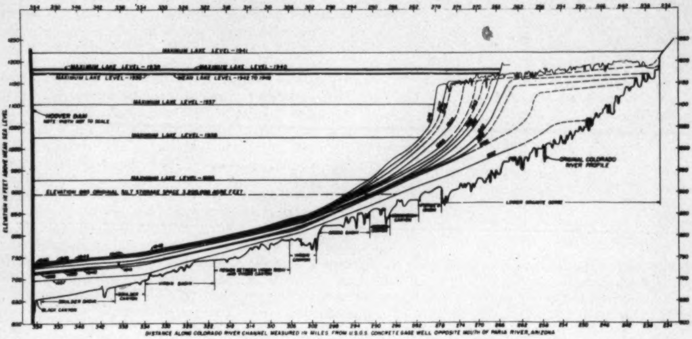
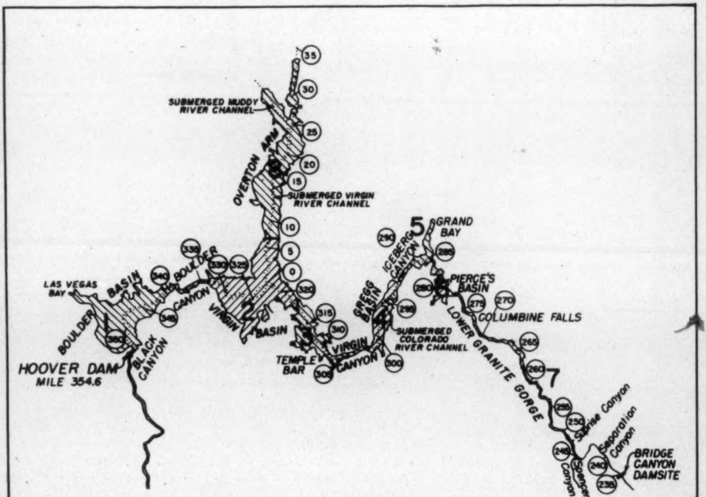


Fig. 1--Profiles of sediment distribution along Colorado River channel through Lake Mead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30
SUBMERGED MUDDY RIVER CHANNEL
25
OVERTON ARM
20
15
SUBMERGED VIRGIN RIVER CHANNEL
10
5
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5
GRAND BAY
290
ICEBERG CANYON
285
LAS VEGAS BAY
BOULDER BASIN
335
340
BOULDER CANYON
330
325
320
PIERCE'S BASIN
280
270
275
COLUMBINE FALLS
345
VIRGIN
2
BASIN
315
GREGG BASIN
295
LOWER GRANITE GORGE
BOULDER
350
BLACK CANYON
310
SUBMERGED COLORADO RIVER CHANNEL
265
HOOVER DAM MILE 354.6
TEMPLE BAR
305
VIRGIN CANYON
300
260
7
255
250
Surprise Canyon
Separation Canyon
245
240
BRIDGE CANYON DAMSITE
Spencer Canyon
235

Fig. 2--Lake Mead

fixed points on shore. The deep-water portion of the survey, utilizing echo-sounding equipment, was in charge of a Navy crew. The shallow portion of the reservoir, above Pierce Ferry, where deep water equipment could not be used, was surveyed by a Bureau of Reclamation crew, using standard river-survey methods.

Table 1--Areas of deposition of sediment

Area[a]	Volume	Total
	ac ft	pct
1	294,700	20.8
2	142,000	10.0
3	59,200	4.2
4	113,600	8.0
5	97,400	6.8
6	144,300	10.1
7	538,200	38.0
8	30,600	2.1
Total	1,420,000	100.0

[a] See Figure 2

The character of the sediment deposits--To determine the characteristics of the sediment deposits, a total of 1600 sediment samples were analyzed from 65 cores of river-bed material. Two types of core sampler were used: one, a gravity sampler of the Emery-Dietz type; the other, a piston sampler which was a modification of an original Swedish sampler used for oceanographic work. Surface samples were obtained by a snapper sampler and also by means of a standard dipper. The shape of the sediment deposits indicated that a regular delta (see Fig. 3) had formed where the river enters the reservoir, that is, in the stretch above Pierce Ferry. The delta consisted of the regular top-set and fore-set beds, with bottom-set beds extending from the front of the delta along the old river channel all the way to the dam. The bottom-set bed consisted of very fine material of low specific gravity and high water content, some near the dam at the top of the deposits containing as much as 80 pct by weight. The top-set beds of the delta consisted of much coarser material of greater unit weight and less water content.

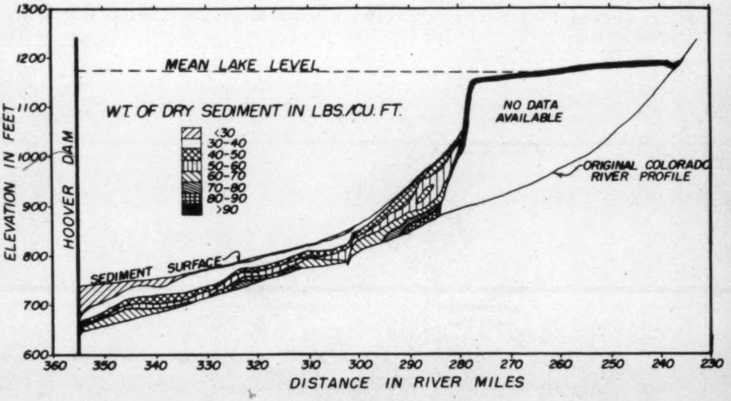

Fig. 3--Specific weight of sediment shown in longitudinal section through Lake Mead

Numerous gas cavities were found in the fine deposits, in places giving the sediment accumulation almost a sponge-like character. From the samples obtained it was estimated that the gas content in place was as high as two per cent by volume. An analysis of the gas showed it to contain the following constituents: 78.0 pct methane, 16.3 pct nitrogen, 4.8 pct oxygen, 0.4 pct argon, and 0.5 pct carbon dioxide. The high content of methane seemed to indicate that decomposition of organic matter was taking place in the sediment mass. This was confirmed by temperature gradients within the sediment, obtained by means of a bathythermograph, which indicated a gradient of as much as ten degrees Fahrenheit for a 40-ft depth. The organic matter's content varied from 0.2 to 1.0 pct.

The dissolved solids--The chemical balance of the reservoir water is still the subject of study, but it has been determined without question that very large quantities of salts, particularly gypsum, are going into solution from the very extensive deposits found along the shores of the lake. It is estimated that more than 1,500,000 tons of salts, mainly gypsum, are going into solution every year. At the same time large quantities of salts are being deposited on the reservoir floor. This is less than the amount of salts which is estimated to go into solution. The possibility exists, therefore, that the average salinity of the lake may increase as the years go by. Both the amount dissolved and the amount deposited are small as compared with the total weight of approximately 10,000,000 tons of dissolved salts entering and leaving the lake each year. Fortunately, it is possible to release water at Hoover Dam at two different elevations and, by selecting according to the vertical salt distribution in the lake at the dam, it is possible to counteract the increase in salinity indicated by the sediment balance figures. Possibly the amount of salts going into solution may decrease as the layers of gypsum are being dissolved and covered by land slides. Careful records are kept of the salinity of water discharged below Hoover Dam and no increase in the average salinity of approximately 650 ppm has been in evidence.

Circulation of the water in the lake--Since early information as to the distribution of sediment within the volume of the lake was obtained from the early density-current observations, special attention was given to the possible establishment of the circulation within the lake at various times of year.

In all, 12 cruises were made between February, 1948, and February, 1949, in course of which salinity and temperature records were collected from about 70 stations throughout the lake. At each station, bathythermographic records of temperature variation with depth were obtained and water samples were secured and analyzed from many depths. By means of these salinity and temperature records, it was possible to identify the currents within the body of the lake without actually measuring the velocities, which usually are very low, less than one-half of a foot per second.

It was determined (see Fig. 4) that circulation conditions in the lake vary with the seasons of the year. During the spring the inflow from snowmelt is high. While the water is cold, it is not much colder than the surface water of the lake, but the salinity is much lower than the salinity of the lake water, approximately 220 ppm as compared with 600 or 700 ppm of the lake water. Sediment content is relatively low. Under these conditions, inflowing water continues downstream below the head of the lake as a surface current, approximately 100 ft thick, and the lake itself, sometimes as far as the Lower Basin, assumes a green appearance as compared with the blue color characteristic of the lake at other seasons of the year. Below the surface current there exists a large roller with downstream velocities in the region below the surface current and upstream velocities along the lake bed.

During summer the inflow is sharply reduced and a larger proportion originates from other than snowmelt sources. As a result the salinity is substantially greater than it was during the

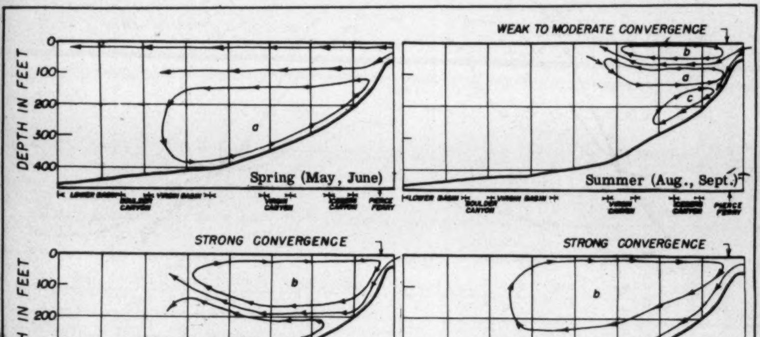

Fig. 4--Indicated circulation for the seasons

spring season, reaching a thousand parts per million at times. The temperature of the inflowing water is about the same as the surface temperature of the lake. The more saline water sinks over the edge of the delta at the head of the lake to a depth of about 80 ft, where it forms a horizontal current on top of the colder water of higher density at greater depth, but below the remnants of the spring inflow water of low salinity immediately below the surface. Occasionally a tongue of very saline water may sink all the way to the bottom of the lake. The result of this flow pattern is a rather confused system of eddies, one of which may be found on the surface with upstream velocities at the water surface and downstream velocities at the top of the main current at a depth of about 80 ft. One or two rollers may exist below the current, depending on the appearance of a tongue of heavy water along the bottom of the lake.

During the fall months, the volume of inflow decreases further while the salinity increases, and the incoming water drops down to greater depth but still not all the way to the bottom of the lake. A distinct top roller exists with upstream velocities along the surface and a marked line of convergence where the incoming muddy water dips down under the surface flow. Below the incoming flow there is a bottom roller with upstream velocities along the bottom of the lake.

During the winter months the temperature of the incoming water is substantially lower than the temperature of the water in the lake and, upon reaching the lake, the incoming water dips all the way to the bottom and continues as a distinct flow along the bottom of the reservoir, while a large roller exists with upstream velocities along the surface and a distinct line of convergence at the face of the delta.

Other investigations--Many other related phenomena were investigated while the sedimentation survey was in progress. Among them was a preliminary investigation of the possible evaporation from the lake's surface as compared with the evaporation indicated by the standard evaporation pans. The results of these preliminary evaporation investigations (see Fig. 5) were so significant that it was decided to initiate a thorough investigation of the entire evaporation phenomenon as a continuation of the sedimentation survey. These investigations are now in progress.

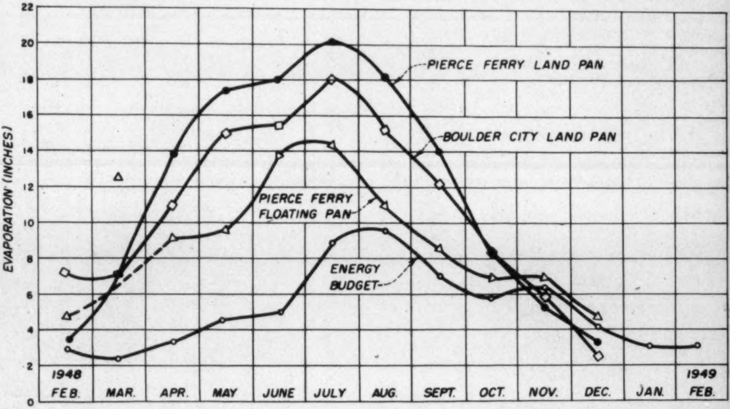

Fig. 5--Evaporation computed from energy budget compared to pan evaporation

In addition, it was decided to determine whether a general lowering of the lake's bed had taken place due to subsidence caused by the enormous weight of water and sediment. The precise leveling carried out around the lake disclosed that the whole country covered by the lake had subsided a maximum of seven inches. More or less by accident, it was discovered at the same time that the city of Las Vegas and the country immediately surrounding it had subsided a maximum of 14 inches during the past 15 years. This particular subsidence has no connection with the super-

imposed weights in the Lake Mead area, but is believed due to increased withdrawal of ground water in the Las Vegas area.

The life of the lake--One of the principal answers which was desired from the sedimentation survey was the estimated period which would elapse before the entire storage volume of the lake was filled with sediment, thus making it useless for storing of floods and for regulating the flow of the river. Taking into account the increasing compaction of the deposited sediment as additional layers are placed on top of earlier deposits, it is estimated that it will be almost 500 years before all storage capacity of the lake has been lost. The useful capacity of the lake will have been reduced to a considerable extent long before that time, unless other storage works are constructed upstream from Hoover Dam long before the operating volume is reduced to any important extent.

Downstream effects--The gradual filling of the storage space of Lake Mead with sediment carried by the upper river is not the only sediment problem introduced by the construction of Hoover Dam and of the other dams downstream, Davis Dam, Parker Dam, and Imperial Dam. Through the centuries the river bed of the Colorado River has adjusted itself to the transportation of large volumes of sediment. In order to move this additional weight, a relatively steep slope downstream was required, steeper than that needed to transport clear water. As Hoover Dam and, later, Parker Dam were closed, and the sediment upstream from those structures was deposited in their respective reservoirs, the water discharged through the dams, or power plants, became clear. Since the transport of clear water required a flatter slope of the river than the transport of a water and sediment mixture, the river bed at once began to readjust its slope so as to conform to the requirements of the clear water. The establishment of the flatter slope downstream meant a lowering of the river bed below the storage dams, that is, below Hoover and Parker Dams and, recently, below Davis Dam.

Before Davis Dam was built, the sediment removed from the river bed in this manner downstream from Hoover Dam was deposited in the reservoir of the dam next downstream, Parker Dam. It is the nature of sediment depositions in reservoirs, however, that the coarser sediment is deposited in the upper reaches of the reservoir, forming a delta similar to that being formed where sediment-laden rivers enter the ocean. The result of the delta formation is that the river bed upstream from the reservoir becomes aggraded, a phenomenon which, over a sufficient length of time, may extend upstream for great distances. The initial result of the interference with the river's flow by the removal of the sediment load is, therefore, that the river bed becomes lowered downstream from dams and increases its elevation upstream from reservoirs formed by dams downstream.

Wherever a gravity diversion had been in existence on a reach of the river where the river bed has been lowered, diversion without a diversion dam may be made impossible. This has been the case with the diversion for the Palo Verde Irrigation District near Blythe. To save this fertile area from destruction due to lack of water, the Congress appropriated funds for the construction of a temporary diversion dam at the intake of the District so as to maintain the water-surface elevation at that point in spite of the general lowering of the river bed below Parker Dam.

On the other hand, should agricultural land be drained to a point on the river where the river bed is increasing its elevation upstream from a dam, the drainage from the land may be seriously affected. This has been the case to some extent at the drainage outlet from the Palo Verde Irrigation District, and temporary river-rectification work has been carried out in that vicinity so as to provide temporary relief pending the construction, at a later time, of a more extensive river-rectification project.

The effect of a large storage dam, such as Hoover Dam, on a sediment-carrying stream is not limited, however, to the lowering of the river bed below the dam and the raising of the river bed above reservoirs created by dams downstream. Serious consequences may also follow the elimination of flood flows which, in the natural state of the river, serve to clean the river bed of accumulated vegetation and even to scour substantial amounts of the accumulated sediment from the bed of the stream. This and other causes brought about by the construction of Hoover Dam, added to the delta formation upstream from Parker Dam reservoir, created a serious situation along the river between the towns of Needles, California, and Topock, Arizona, where a true river bed had ceased to exist and the water found its way through innumerable channels and sloughs creating a virtual swamp.

To remedy this condition and to protect the city of Needles and the Santa Fe Railroad, which parallels the river between Needles and Topock, the Government initiated a dredging program in 1948 for the purpose of creating a new, unobstructed river channel from Needles to Topock. This project is nearing completion and the water surface at Needles has already dropped some six feet, with the result that large areas of land adjacent to the river, which were formerly waterlogged, are now suited for the growing of crops.

It will be realized from this summary of the problems that have arisen on the Colorado River that the mere construction of one or more storage dams to control the floods and the sediment loads does not prevent many other problems from arising which require extensive and continuous remedial works and maintenance.

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THE EFFECT OF SURFACE HEAD ON INFILTRATION RATES BASED ON THE PERFORMANCE OF RING INFILTROMETERS AND PONDS

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Abstract--Studies with infiltrometers and small ponds indicate that the normal relatively low infiltration rates of certain soils may be increased by providing sufficient depth of water or surface head on the soil surface. Infiltration rates increased directly proportional to head motivating flow in infiltrometers and ponds on untreated soil under water-spreading conditions. Hydraulic head loss and length of saturated soil column explain why greater increases in infiltration rates occurred with increases in surface head on untreated soil than on a soil rendered more permeable by treatment. Hydraulic head losses were obtained with infiltrometers equipped with manometers located 1 1/2, 4 1/2, and 7 1/2 inches below the soil surface. The resistance of untreated soil to flow reduced the total head motivating flow to a negligible amount at a depth of 7 1/2 inches below the soil surface. Where hydraulic head exists at the bottom end of an infiltrometer extending into the soil, the need for a "balanced buffer" rather than a "partial buffer" or an "excessive buffer" to prevent lateral flow is discussed. Piezometric heads in relatively pervious soil horizons below the soil surface within and outside of a pond are reported.

Introduction

Tests of the effect of surface head on infiltration rates were performed near Wasco, California, on Hesperia sandy loam, which has a relatively low infiltration rate as compared to soils generally considered suitable for water spreading. However, this soil is representative of many of the soils of the San Joaquin Valley and many other areas where water has been spread or where water spreading is contemplated to augment ground-water supplies. Because of the agricultural value of the soil it is desired to increase the infiltration rates in order (1) that only a reasonable portion of the land area be designated for water spreading and (2) to localize fairly large quantities of water in a given area. The infiltration rate depends largely upon soil characteristics and operational procedures. This rate may be affected by treatment of the soil, [MUCKEL, 1951]. For example, the use of cotton gin trash and Bermuda grass has increased infiltration rates. Some effects of treatments and factors involved are discussed by BLISS and JOHNSON [1952]. Included in operational procedures is the depth at which water is maintained on the soil surface, called surface head. The effect of surface head depends upon the hydraulic head loss in a given length or depth of saturated soil. The hydraulic head includes the surface head. It is possible that for certain soils and topography, sufficient increase in infiltration rates may be obtained by increasing the surface head over the head normally used. This may eliminate the need for expensive soil treatments. The problem is an economic one, where costs must be related to benefits derived.

The problem

The average infiltration rate found during a period of prolonged submergence in this area and other problem areas is less than one foot a day. An increase in this rate to one and a half feet per day by soil treatment or operational procedure has been considered reasonably satisfactory, although higher rates are desirable. The problem is to determine the effect of increases in surface head on the infiltration rate using infiltrometers and small ponds as test units. Much of the flow on a large area moves vertically downward and the least pervious soil horizon will control and limit the infiltration rate. A large area may be considered to consist of many small test units, the flow from the inner units being confined more or less to vertical flow downward by the outer units, the effect diminishing with distance from the center. Beneath small test units, flow may move laterally as well as vertically. In order to relate the results obtained with small test units to the performance of large spreading areas it is necessary to either prevent or account for lateral flow from small units, when such flow enters the problem.

Procedure

The experimental procedure may be divided into three parts. The first deals with experiments involving the effect of surface head on infiltration rates and includes the use of buffers.

The second is concerned with hydraulic head losses within the soil as obtained directly from field installations. The third deals with soil characteristics based on laboratory studies of samples taken from the test ponds used in the studies.

Part 1 - Effect of surface head on infiltration rates--The tests were performed on Hesperia sandy loam which is a recent to young alluvial soil showing slight profile development. The upper subsoil layers are like the surface soils although the material shows changes in texture due to stratification. Of necessity, the determination of the effect of surface head on the infiltration rate was limited to a study of unbuffered (single ring) and buffered (double ring) infiltrometers and small test ponds as shown in Table 1. A pool of water in a second ring around an inner ring is referred to as a buffer.

Table 1--Test units used in studies of the effect of surface head on infiltration rates

Test Unit	Shape	Area	Provisions for buffering	Soil treatment	Remarks
		sq ft			
Inner concentric Pond 1	Circular	218	Yes	None	Within outer 1
Outer concentric Pond 1	Circular	653	No	None	....
Inner concentric Pond 2	Circular	218	Yes	None	Within outer 2
Outer concentric Pond 2	Circular	653	No	None	....
Pond 10	Rectangular	218	No	None	....
Infiltrometer 1	Circular	0.78	Yes	None	Within inner 1
Infiltrometer 2	Circular	0.78	Yes	None	Within inner 1
Pond 17	Rectangular	218	No	Cotton gin trash	....
Infiltrometer 3	Circular	0.78	Yes	Cotton gin trash	Within Pond 17
Infiltrometer 4	Circular	0.78	Yes	Cotton gin trash	Within Pond 17

The surface head was varied by increments from about 0.5 to 1.6 feet on the four concentric ring ponds, from 0.35 to 2 feet on Pond 10, from 0.7 to 1.7 feet on Pond 17, and from 0.6 to 4.5 feet on the two infiltrometers within inner concentric Pond 1 and on the two infiltrometers within Pond 17.

Well water was used in all cases. Surface head and flow into the infiltrometers and ponds were regulated by adjustable float controlled valves. Water was supplied at a rate at which water could pass through the soil surface into the soil mass at a given surface head. In water spreading this rate has been referred to by a number of terms, one of which is the infiltration rate. Many consider this rate to be the infiltration capacity. Flow into infiltrometers was measured by volume changes in calibrated supply tanks. Flow into ponds was measured by commercial water meters. Figures 1 and 2 show the general setup of infiltrometers within untreated inner concentric Pond 1 and cotton-gin-trash Pond 17, respectively.

Water was supplied continuously to ponds used for surface head tests. A given surface head on a pond was allowed to remain for a period of time, usually several days. During this period there is a normal decline in infiltration rate because of increased clogging. To compare the effect of an increase in surface head over the previous surface head this normal decline in infiltration rate was added to the infiltration rate obtained for the increased surface head. To compare the effect of the various surface heads, the normal decline in infiltration rate with time was based on a constant surface head and the initial infiltration rate associated with this surface head.

Part 2 - Hydraulic head losses within the soil and length of soil column--Each infiltrometer was provided with three holes located 1 1/2, 4 1/2, and 7 1/2 inches from the bottom end. A short

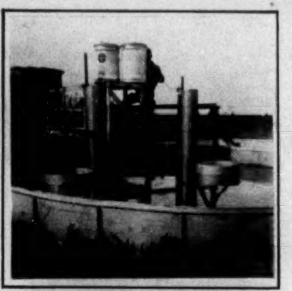

Fig. 1--Infiltrometers and soil sampling rings within untreated inner concentric Pond 1

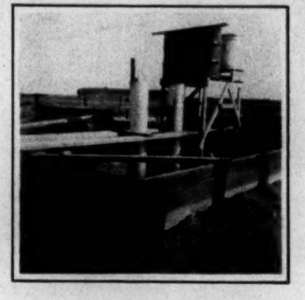

Fig. 2--Infiltrometers within cotton-gin-trash Pond 17

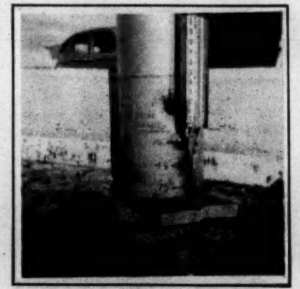

Fig. 3--Infiltrometers equipped with manometers

L-shaped nipple was connected to each hole. The nipple did not project inside. A Tygon tubing connection between each nipple and a glass tube formed a manometer arrangement as shown in Figure 3. When the infiltrometers were forced into the soil to a depth of nine inches, manometers indicated the hydraulic head 1 1/2, 4 1/2, and 7 1/2 inches below the soil surface. Only enough soil was removed for the nipples to move downward freely. Soil was then replaced around nipples and Tygon tubes. Manometer readings were also used to determine hydraulic head losses between various soil levels and soil sections of greatest resistance or friction.

The Darcy equation which states that the velocity of flow through a column of saturated soil is equal to the difference in pressure head at the ends of the column divided by the length of the column and then multiplied by a proportionality constant was applied to the data. Water temperatures for all experiments were between 60 and 70° F and seasonally consistent, consequently no corrections were made for temperature.

Part 3 - Some soil characteristics--Soil samples were taken inside small metal rings (see Fig. 1) temporarily installed within inner concentric Pond 1 and Pond 17. These samples were taken for depths of 0 to 1 1/2, 1 1/2 to 4 1/2, and 4 1/2 to 7 1/2 inches. These depths correspond to distances between manometer locations. Volume weights were determined and sieve analyses of primary particle sizes made. To approximate the organic matter content of the soil on the sieves, each sieve was immersed in water and shaken, and the organic matter allowed to float off. This process was repeated three times in fresh water. Loss in weight was considered to represent the major portion of the organic matter present. Material passing the 0.1 millimeter screen was heated to 1000° F for four hours and the loss in weight was used to estimate the organic matter.

Field capacity was determined by sampling the soil on consecutive days after the pond water had drained from the small metal rings and the inner and outer concentric ponds. The 0 to 4 1/2 and 4 1/2 to 7 1/2 inch depths were sampled. These samples were taken from an area enclosed by a metal ring which was covered to reduce evaporation. As soon as the soil moisture content became reasonably constant the value obtained was considered to be the field capacity. Saturation was obtained by determining the soil moisture content of samples that had been soaked in a water bath. The "non-capillary" pore space through which saturated flow chiefly moves was obtained by the difference between field capacity and saturation.

Results and interpretation

Figure 4 shows the increase in infiltration rates for untreated soil as the surface head was increased for five cases. The surface head was used in plotting the data since it represents head that can be measured readily and controlled in the operation of a spreading area. Two curves are shown for each test run. The lower curve represents increases in infiltration rate as surface head increases, with no adjustment for the normal decline over the period of time required for each test run. The upper curve, in each case, was adjusted for the normal decline.

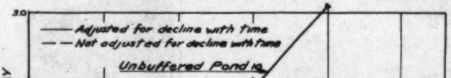

Fig. 4--Increases in infiltration rate with increases in surface head

Actually the head motivating flow is somewhat greater than the surface head shown in Figure 4. That is, to the surface head must be added the length of the saturated soil column. For example, to the surface head for inner concentric Pond 1 and Pond 10, approximately 0.24 foot and 0.55 foot must be added, respectively. When these values are added to the surface heads shown in Figure 4, the infiltration rates are approximately directly proportional to the head motivating flow. That is, doubling the head motivating flow essentially doubles the infiltration rate. The values of 0.24 and 0.55 foot were calculated from the ratio of the infiltration rate for a given surface head to the infiltration rate for an increased surface head, using the Darcy equation.

Little change seemed to occur in infiltration rates in the inner ponds of the concentric rings whether or not the outer ponds were used as buffers. For example, at one time the outer pond was turned off when the infiltration rate for the inner pond was 1.0 foot per day for a surface head of 1.6 feet. The infiltration rate in the inner pond increased by only 0.04 foot per day.

Table 2 shows the increase in infiltration rates with increases in surface head for Infiltrometer 1 located within inner concentric Pond 1. The pond and infiltrometer were continuously flooded for dates shown as well as dates omitted. Results for Infiltrometer 2 are not shown as they were within five per cent of the results obtained with Infiltrometer 1. Inner concentric Pond 1 had been running for some time prior to the installation of Infiltrometers 1 and 2 and the infiltration rate had declined to about 0.6 foot per day. Infiltration rates in the infiltrometers were somewhat higher than this, probably because of surface distrubances or slight differences in conditions at their locations. The hydraulic head and hydraulic head losses shown in Table 2 are referred to

Table 2--Head, head losses and infiltration rate relationships, and proportionality constant for Infiltrometer 1

Date	Surface head		Hydraulic head at 7 1/2"	Loss in hydraulic head between soil levels				Infiltration rate		Proportionality constant
	Inner Pond 1	Infiltrometer		0 to 1 1/2"	1 1/2 to 4 1/2"	4 1/2 to 7 1/2"	0 to 7 1/2"	Inner Pond 1	Infiltrometer	
1951	ft	ft	ft	ft	ft	ft	ft	ft/day	ft/day	
Nov. 15	0.70	0.63	...	0.10	...	...	...	0.57	0.80	...
16	0.70	1.70	0.31	0.17	0.78	1.06	2.01	0.54	1.20	0.37
29	0.68	1.68	0.18	0.14	0.77	1.21	2.12	0.41	0.94	0.27
30	0.68	2.67	0.62	0.20	0.97	1.50	2.67	0.40	1.10	0.26
Dec. 1	0.68	2.67	0.61	0.20	0.90	1.58	2.68	0.39	1.14	0.26
3	0.68	2.67	0.54	0.19	0.98	1.58	2.75	0.38	1.11	0.25
4	0.68	3.67	1.19	0.24	1.20	1.66	3.10	0.38	1.23	0.25
6	0.68	3.68	1.08	0.25	1.18	1.79	3.22	0.37	1.30	0.25
11	0.69	3.72	1.09	0.28	1.19	1.78	3.25	0.33	1.10	0.21
12	0.69	4.67	1.43	0.31	1.02	2.53	3.86	0.33	1.34	0.22
14	0.68	4.66	1.36	0.21	1.08	2.63	3.92	0.32	1.45	0.23
17	drying	4.66	1.30	0.30	1.01	2.67	3.98	drying	1.46	0.23
18	dry	4.66	1.09	0.32	0.87	3.00	4.19	dry	1.56	0.23
24	dry	4.66	1.06	0.32	0.81	3.09	4.22	dry	1.25	0.18

the 7 1/2 inch soil level as the datum. Hydraulic head losses in Infiltrometer 1 are greatest between the 4 1/2 to 7 1/2 inch soil levels. However, hydraulic head losses, probably more representative of the general conditions found, were greatest between the 0 to 1 1/2 inch soil levels in Infiltrometer 2. The maximum hydraulic head at the 7 1/2 inch level for a surface head of 1.70 feet was only 0.31 foot. Usually the concentric ponds have been run at a surface head of about 0.70 foot and the pond borders extend 9 to 13 inches into the soil. Based on hydraulic heads at the 7 1/2 inch level for Infiltrometer 1, even at the maximum surface heads shown in Table 2, there would appear to be little hydraulic head to force water laterally at the bottom of the borders extending into the soil. This is probably why infiltration rates, for the range of infiltration rates and surface heads investigated in the inner pond, do not appear to be affected by the outer pond whether it is used as a buffer or not. For higher rates of infiltration, such as exist during the early portion of concentric pond runs, sufficient hydraulic heads may exist below the bottom of the pond borders to cause appreciable lateral flow. A study of the performance of the untreated concentric ponds and larger untreated areas shows that only initial rates of infiltration are higher in the concentric ponds. This indicates that there may be considerable lateral flow in the ponds only until sufficient soil clogging occurs to reduce hydraulic heads to negligible value at the bottoms of the pond borders.

The data appear to indicate that for soils of high resistance to water movement a single ring or unbuffered infiltrometer is suitable if it extends into the soil to a depth where hydraulic head becomes negligible. This of course presupposes that lateral movement caused by capillary forces may be neglected as in water spreading. If there are soil conditions below the end of the ring infiltrometer which cause the hydraulic head to build up, a buffer might be helpful, but even then some of the lateral flow would probably be supplied by the inner ring.

Figure 5 shows increases in infiltration rates, corrected for normal decline, with increases in surface head for Infiltrometer 1. Because of surface head limitations in inner concentric Pond 1, Infiltrometer 1 was only partially buffered. However, for the infiltration rates and associated hydraulic heads it is believed complete buffering would have had little effect. Increases in infiltration rates are reasonably consistent with the performance of Pond 10 and the concentric ponds for surface heads up to 1.7 ft. For higher heads, infiltration rate increases were not as great but still consistent with the losses in hydraulic head. That is, ratios of infiltration rates were reasonably similar to ratios of hydraulic head losses on successive days. The proportionality constant decreased considerably during the time interval following the increase of surface head above 1.7 ft. Other factors seem to have changed and consequently changes in infiltration rates cannot be attributed entirely to changes in hydraulic head. When the water was shut off in inner concentric Pond 1 there was little increase in infiltration rate in Infiltrometer 1, noted as the unbuffered section of Figure 5.

Table 3--Head, head losses and infiltration relationships, and proportionality constant for Infiltrometer 3

Date	Surface head		Hydraulic head at 7 1/2"	Loss in hydraulic head between soil levels				Infiltration rate		Proportionality constant
	Pond 17	Infiltrometer		0 to 1 1/2"	1 1/2 to 4 1/2"	4 1/2 to 7 1/2"	0 to 7 1/2"	Pond 17	Infiltrometer	
1952	ft	ft	ft	ft	ft	ft	ft	ft/day	ft/day	
Feb. 4	0.45	0.69	0.72	0.06	0.25	0.28	0.59	9.30	8.40	8.8
5	1.02	0.70	1.09	0.03	0.10	0.10	0.23	11.4	4.31	11.6
8	0.46	0.69	.....	0.09	0.06	.....	.....	11.5	8.67	.....
Mar. 3	0.74	0.69	.....	0.08	0.27	.....	.....	10.2	9.53	.....
3	0.68	2.79	1.37	0.13	0.47	1.44	2.04	10.2	21.3	6.5
6	0.69	2.79	1.50	0.04	0.29	1.58	1.91	9.10	20.0	6.5
6	0.94	4.33	2.37	0.23	0.20	2.15	2.58	9.10	30.3	7.3
9	0.92	0.98	.....	.....	.....	.....	.....	8.93	11.1	.....
12	0.98	0.96	.....	0.06	0.39	.....	.....	9.32	9.57	.....
13	1.68	1.69	0.77	0.05	0.49	1.00	1.54	12.1	11.4	4.6
14	1.74	1.73	0.74	0.10	0.49	1.02	1.61	12.9	11.7	4.5
16	1.70	1.69	0.72	0.06	0.49	1.04	1.59	11.5	10.8	4.2
18	1.71	1.68	0.75	0.09	0.48	0.98	1.55	11.9	11.4	4.6
22	Dry	1.67	.....	.....	.....	.....	.....	Dry	18.8	.....
23	Dry	1.67	0.01	0.03	0.66	1.59	2.28	.....	17.2	4.7
25	Dry	0.68	.....	.....	.....	.....	.....	.....	13.1	.....
26	Dry	4.31	1.46	0.02	0.83	2.62	3.47	.....	36.7	6.6

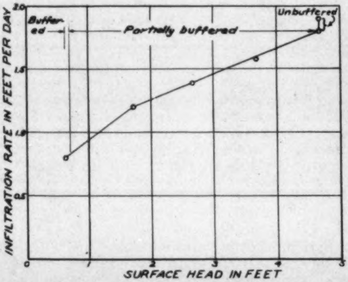

Fig. 5--Increases in infiltration rate with increases in surface head for infiltrometer 1

Table 3 shows data for Infiltrometer 3 and cotton-gin-trash Pond 17. For both Infiltrometers 3 and 4 within Pond 17, greatest hydraulic head losses occurred between the 4 1/2 to 7 1/2 inch soil levels. For equivalent surface heads, greater hydraulic heads were recorded on the 7 1/2 inch level in the cotton-gin-trash pond than in the untreated pond. The proportionality constant is much higher for the soil treated with cotton gin trash than for the untreated soil. Water moving as saturated flow probably is in contact with a greater surface area of particles in the untreated soil which causes greater friction as compared to the well-aggregated soil treated with cotton gin trash. The coatings surrounding soil particles, produced by the drying of the by-products of microbial decomposition of the cotton gin trash, probably provide much less friction to flow than do the soil particles of the untreated soil. Results for Infiltrometer 4 were reasonably similar to results for Infiltrometer 3. Surface head did not cause additional clogging due to compaction or some other factor as indicated by the data within the limits investigated. When a low surface head was followed by a higher surface head and returned to the same low surface head, all within a short period of time, the infiltration rates for the low surface heads were reasonably similar.

Figure 6 shows relationships between surface head and infiltration rate for Infiltrometer 3 for three tests. Curve C was extended as shown by the dashed line. The surface head in the pond could not be raised beyond 1.7 feet. The data reflect the short period of time involved and no correction for decline seemed necessary. For the unbuffered test, Pond 17 was still moist enough for capillary influence to be considered negligible. Infiltration rates appear to be approximately directly proportional to the hydraulic head, except for the buffered run. The higher rates of Curves A and B appear to be due to lateral flow caused by unequal hydraulic heads which establish a gradient at the bottom of the infiltrometer. For the buffered conditions, Curve C, the hydraulic head of the infiltrometer and buffer tend to balance and flow is confined largely to vertical movement downward. Data indicate excessive buffering reduced the infiltration rate in the infiltrometer. For example, on February 4 and 5 the change in surface head from 0.45 to 1.02 ft in Pond 17 caused a decline in infiltration rate from 8.4 to 4.3 ft per day in Infiltrometer 3. The hydraulic head increased from 0.72 to 1.09 ft at the 7 1/2 inch level in the infiltrometer, although the surface head in the infiltrometer remained reasonably constant. The differential pressure in the 7 1/2 inch soil column within the infiltrometer was reduced.

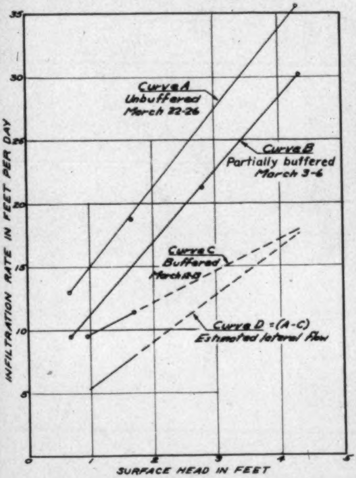

Fig. 6--Increases in infiltration rate with increases in surface head and estimated lateral flow for infiltrometer3

Curve D of Figure 6 is the difference between Curve A and Curve C. Curve D may be considered to represent subsurface lateral flow from Infiltrometer 3. For the conditions existing, the infiltration rate of Pond 17 was about ten feet per day with a surface head of one foot. Figure 6 indicates a lateral flow correction of about five feet for a surface head of one foot due to hydraulic head at the bottom of Infiltrometer 3. If this correction were applied to Pond 17 the infiltration rate would be reduced to five feet per day and might thus be more representative of a large area. This correction based on hydraulic head, is probably somewhat high as Pond 17 is greater in area than Infiltrometer 3 and consequently lateral flow should be less. Correcting for lateral flow, increases in surface head would appear to be less effective in increasing infiltration rates on the treated pond than on the untreated pond.

Figure 7 shows piezometric pressures in various "soft" and "hard" horizons underlying Pond 17. Water elevations are to scale, but the thicknesses of horizons indicated are not to scale. The hard horizons appear to be less permeable, as indicated by the build up of water above them. There appears to be lateral flow in the soft horizons as indicated by the gradient between piezometers B and G located in a soft horizon. Another reduction in the infiltration rate of Pond 17, based on the percolation rate of lower horizons, would appear necessary. Piezometric pressure which may exist above a hard horizon is reduced by friction until it is eliminated at some point within the hard horizon. Below this point flow is largely downward under the influence of gravity.

Table 4 shows some soil properties for untreated and treated ponds. Of particular interest is the 28.5 pct by volume of non-capillary pores in a soil depth of 0 to 4 1/2 inches in cotton-gin-trash Pond 17, as compared to 19 pct in the same depth in untreated inner concentric Pond 1. Volume weights are higher in the untreated pond. There is considerably more organic matter in Pond 17. Volume weight increases with depth in Pond 17 and below the treated zone approaches the value found in the untreated pond. In the treated pond, cotton gin trash was originally spaded into the soil to a depth of approximately six inches. The soil below this level appears reasonably the same as untreated soil, particulary as depth increases. It would seem that the soil below the six-inch level would control and infiltration rates would not be as high as found. It is possible that the interface between water and soil and the transition zone between the treated and untreated soil below are extremely important. A stable transition zone of low resistance, such as created by the cotton gin trash, may be as significant as its influence in creating large stable pores where located.

Summary and conclusions

The head motivating flow for many untreated soils is made up largely of surface head. Little head will develop within such soils because of their high resistance to flow. Under such conditions, as exemplified locally, infiltration rates are relatively low for surface heads normally used in water spreading. Tests on untreated soil indicate increases in infiltration rate were directly proportional to increases in the head motivating flow for the range of surface head used.

Table 4--Some properties of soil obtained from test units

Depth	Satura-tion	Field capac-ity	Non-capil-lary pores	Volume Weight	Sieve analysis Size classes in millimeters						Organic matter
					>2	<2>1	<1>0.5	<0.5>0.25	<0.25>0.1	<0.1	
inch	pct by volume	pct by volume	pct by volume	gm/cc	pct	pct	pct	pct	pct	pct	pct
Inner concentric Pond 1 (untreated)											
0 - 1 1/2	55	...	...	1.59	1.3	6.9	12.3	16.4	25.6	37.5	1
1 1/2 - 4 1/2	41	...	...	1.58	2.0	7.1	13.1	17.5	25.5	34.8	< 1
4 1/2 - 7 1/2	39	22	17	1.66	1.4	7.4	13.0	17.7	26.8	33.7	< 1
0 - 4 1/2	46	27	19	...	...	...	...	...	...	...	< 1
Pond 17 (treated with cotton gin trash)											
0 - 1 1/2	55	25	30	0.88	5.4	10.7	13.4	18.8	21.6	30.1	18
1 1/2 - 4 1/2	53	26	27	0.96	3.6	8.9	13.5	18.9	23.0	32.1	18
4 1/2 - 7 1/2	39	23	16	1.27	3.9	10.5	14.4	21.2	23.0	27.0	9
12 - 14	...	...	...	1.55	4.2	11.8	18.4	23.7	21.2	20.7	<1

For a given surface head and length of saturated column, greater losses in hydraulic head were found in untreated soil than in treated soil. In a soil with higher infiltration rates due to treatment the saturated soil column appears to be longer than in the untreated soil. The longer the saturated column the less effective a given increase in surface head will be in increasing the infiltration rate. However, it would not be economically sound to treat surface soil or use operational procedures that can establish a higher infiltration rate than the percolation rate of lower soil horizons.

Little lateral flow occurred from infiltrometers and small ponds on untreated soils for the infiltration rates and low hydraulic heads found. Where little hydraulic head exists at the bottom of an infiltrometer, a single ring or unbuffered infiltrometer may be considered reasonably representative of a large area if no lateral flow takes place on lower less-pervious horizons. Where hydraulic head existed at the bottom of a ring it was found desirable to balance this with an equal

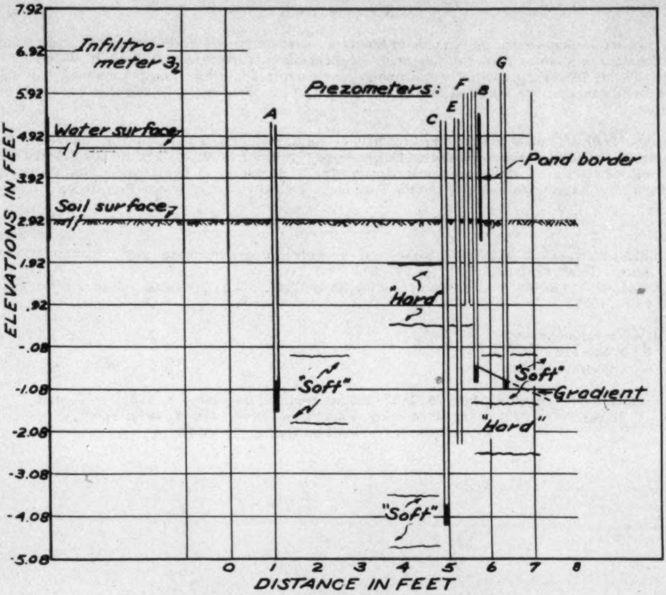

Fig. 7--Piezometric pressures in various soil horizons on March 16 illustrating a lateral flow gradient for Pond 17

hydraulic head established by a buffer or outer ring by using equal surface heads in both rings. This may be considered a "balanced buffer." A lower surface head in the outer ring is considered a "partial buffer" and a higher surface head in the outer ring is considered an "excessive buffer." A partial buffer only partially prevented lateral flow from the inner ring since it established a lower hydraulic head than the hydraulic head to be balanced. An excessive buffer reduced the normal downward flow in the inner ring since it established a greater hydraulic head than the hydraulic head to be balanced. If a less pervious soil horizon underlies a buffered ring, water flowing laterally over this horizon is partially supplied by the inner ring as well as the buffer and the value of the buffer is reduced. Piezometers were helpful in determining lateral flow in the vicinity of a test unit.

Soil characteristics accounting for the high infiltration rates on treated soil as compared to untreated soil appear to be a greater volume of non-capillary pores, organic matter indicative of a more stable structure, better entrance conditions with a more stable interface at the soil surface, and a surface soil medium which seems to create a good transition into the untreated soil below. It is also possible that the coatings produced around soil particles by the drying of the byproducts of microbial decomposition of such a material as cotton gin trash offer less resistance to flow than untreated soil.

The growing interest in water spreading as a means of replenishing ground-water supplies partially prompted this report based on an exploratory study. It is believed the need for further study and development of fundamental knowledge is apparent.

Acknowledgment

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FORMATION OF CALDERAS AND MAGMATIC EVOLUTION

Hisashi Kuno

Abstract--Japanese calderas may be classified into two types. The first type includes calderas formed by collapse following the eruption of a tremendous amount of pumice (calderas of Krakatau type of H. Williams). The second type includes those formed without the pumice eruption (calderas of Glencoe type of H. Williams). In both types, post-caldera eruptions build up cones or domes, usually inside the calderas but sometimes on their margin. Most of the pre-caldera lavas consist of rock series originating through fractional crystallization of basaltic magma. In the calderas of Krakatau type, the post-caldera lavas comprise a rock series formed through contamination of the same magma by granitic material, whereas in those of Glencoe type the post-caldera lavas represent an advanced stage of crystallization of the pre-caldera lavas. In the former type, the explosive eruption of the pumice probably shattered the roof of the magma reservoir and facilitated the contamination, whereas in the latter the subsidence took place along a simple system of ring fissures without fracturing of the subsided mass and without giving opportunity for contamination.

Introduction--The term caldera is defined here as a crater-like depression more than two kilometers across formed by collapse or subsidence of the center of a volcanic cone. Similar depressions formed simply by explosion or erosion are not considered here, although they are also included under the term caldera by WILLIAMS [1941].

The mechanism of formation of calderas has been discussed by WILLIAMS [1941], but the writer is particularly interested in the relation which might exist between the mechanism of their formation and the process taking place in the underlying magma reservoir. For this purpose several representative calderas of Japan were studied in the field and also by petrologic work in the laboratory. This paper presents the results of this study together with references to the calderas of Crater Lake, Hawaii, and Mull.

Structure of Japanese calderas--There are at least 16 calderas in the Japanese Islands [KUNO, 1952], and perhaps more than 20 if those of doubtful origin are included. In addition, there are many similar depressions with diameters about two kilometers or a little less, such as found in Akagi and Haruna volcanoes, lying NNW of Tokyo. They might have been formed either by the collapse or by scaling off of the walls of the ordinary craters.

The calderas may be classified into two types. The first type corresponds to the calderas of Krakatau type of WILLIAMS [1941]. They were formed by a collapse following eruption of a tremendous amount of pumice, usually in the form of pumice flows or *nuées ardentes*. Such calderas are therefore surrounded by extensive areas of unstratified pumice-flow deposits or welded tuff. Most of the Japanese calderas belong to this type; for example, the caldera lakes of Sikotu and Toya in southwestern Hokkaido, the caldera lakes of Towada and Tazawa and the caldera of Onikobe in northern Honsyu, the younger caldera of Hakone, southwest of Tokyo, and the four calderas in central and southern Kyusyu [MATSUMOTO, 1943].

The calderas of the second type are not associated with pumice deposits or welded tuff, and are generally smaller in diameter than those of the first type. They were probably formed by subsidence along ring fissures and therefore correspond in their mode of formation to the calderas of Glencoe type of WILLIAMS [1941]. The examples are the older caldera of Hakone and the calderas of Osima and Hatizyo-zima, both in the Izu Islands.

In the Hakone and Towada calderas, a thick series of lavas and pyroclastic rocks was erupted before the outflow of the pumice, whereas in the Onikobe caldera no pre-pumice eruption can be recognized. In other calderas of the first type, the products of the pre-pumice eruption might be present, but they have not been studied sufficiently. In Aso caldera, central Kyusyu, andesitic lava flows are exposed on the caldera wall just below the horizon of welded tuff. However, these lava flows were regarded by MATSUMOTO [1943] as belonging to the older volcanoes lying outside the caldera.

In most calderas of the first type, the collapse was followed by renewed volcanic activity which built up small volcanoes either inside the calderas or on their margin. These post-caldera volcanoes are usually lava domes but sometimes stratovolcanoes, and are generally more steep-sloped than the pre-caldera cones, indicating high viscosity of the magma.

In the calderas of the second type, both the pre- and post-caldera eruptions gave rise to stratovolcanoes or shield volcanoes.

Differentiation and contamination in the magma of Izu and Hakone--In a previous paper [KUNO, 1950c], the writer distinguished two series in the volcanic rocks of Izu and Hakone. The pigeonitic rock series includes rocks formed by fractional crystallization of primary basaltic magma, whereas the hypersthenic rock series includes those originated through contamination of the same magma by granitic material. This conclusion was based chiefly on the observations of the rocks under the microscope. Thus the basic rocks of the latter series occasionally contain quartz xenocrysts together with partially remelted xenocrysts of plagioclase, whereas in the intermediate to acidic rocks of the same series, the quartz crystals are entirely resorbed by the magma and the plagioclase xenocrysts are regrown to ordinary phenocrysts with dust inclusions in the cores or in the intermediate zones which resulted from incipient melting along cleavages.

Since the publication of the paper, many new chemical analyses have been made on the rocks of the region; nearly 200 analyses are now available among which about 70 are those of non-porphyritic or nearly non-porphyritic rocks. From these analyses, the mode of formation of these two rock series has been discussed [KUNO, 1950b]. The conclusion is also presented below.

The SiO_2 percentage in the pigeonitic rock series ranges from 48 (45 if porphyritic rocks are included) to 76, whereas that in the hypersthenic rock series varies from 52 to 77. In the former series basalt and basic andesite are far more abundant than acidic andesite and dacite, whereas in the latter series intermediate andesite is most abundant.

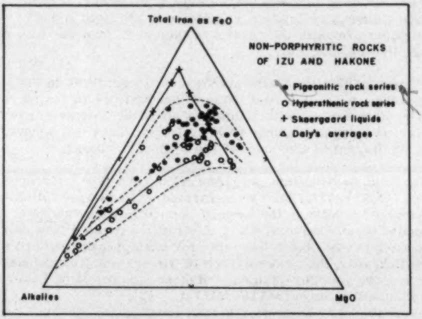

Fig. 1--Trends of variation of the non-porphyritic rocks of Izu and Hakone, the Skaergaard liquids, and DALY's [1914] averages of basalt, andesite, dacite, and rhyolite

In Figure 1 are plotted the ratios MgO to total iron as FeO to alkalies calculated from the analyses of rocks containing less than ten per cent phenocrysts. Total iron is used here instead of FeO of the original diagram by WAGER and DEER [1939] because the degree of oxidation of iron is always higher in volcanic rocks than in the corresponding intrusive rocks, as pointed out by WALKER and POLDERVAART [1949], and therefore the amount of FeO in the volcanic rocks cannot be compared directly with that in the intrusive rocks.

In Figure 1 are also plotted the same ratios of the Skaergaard liquids [WAGER and DEER, 1939] and the DALY's [1914] averages of basalt, andesite, dacite, and rhyolite.

The pigeonitic rock series shows a trend of variation close to that of the Skaergaard liquids, whereas the hypersthenic rock series shows a trend of variation almost coinciding with that of Daly's averages. The rocks of the two series lie within two different zones bounded by dotted lines in the figure, although there are a few exceptions. The trend of variation of the pigeonitic rock series nearly coincides with those of the Karroo dolerites [WALKER and POLDERVAART, 1949] and the Normal Magma Series of Mull [BAILEY and Others, 1924; see Fig. 5 of this paper].

The slight deviation of the trend of variation of the pigeonitic rock series from that of the Skaergaard liquids may be explained as due to the following three factors: (a) the difference of the compositions of the original magmas, (b) comparatively high degree of fractionation in the feldspar series, and (c) comparatively early separation of magnetite in the pigeonitic rock series.

The two points lying at the magnesian end of the pigeonitic rock series in Figure 1 may be taken as representing the original magma of this series. The rocks represented by these points have compositions very close to each other. The average composition of the two is given in Table 1, Col. B. Figure 1 suggests, however, that the ultimate primary magma of the pigeonitic and hypersthenic rock series would have a composition a little more magnesian and less alkaline than the assumed original magma, although rocks of such composition have not been found in Izu and Hakone. Most probably the composition given in Table 1, Col. B, represents the least differentiated stage of the ultimate primary magma.

In Column A is shown the composition of the original magma of the Skaergaard intrusion. The original magma of the pigeonitic rock series of Izu and Hakone is less aluminous and alkaline than-the Skaergaard original magma, but is higher in ferric oxide.

The difference in the content of alkalies gave rise to a difference in the composition of plagioclase separated from the magmas at the beginning of crystallization. Thus the earliest plagioclase in Izu and Hakone is pure anorthite [KUNO, 1950c]. It changes its composition as the crystallization proceeds, but does not become more sodic than bytownite even when the composition of the normative feldspar of the magma attains to calcic andesine. The earliest plagioclase in Skaergaard is medium bytownite [WAGER and DEER, 1939]. The separation of the calcic plagioclase in the early to middle stages of crystallization in Izu and Hakone would have resulted in the higher degree of fractionation in the feldspar series, so that an enrichment of alkalies took place in these stages and continued to the latest stage.

The higher degree of oxidation of iron in the pigeonitic rock series is probably the primary cause of the comparatively early separation of magnetite. In this series, magnetite phenocrysts first appeared in the rocks represented by points lying close to the second liquid of Skaergaard in Figure 1, whereas in the Skaergaard intrusion magnetite first began to separate as a primary precipitate when the magma attained the composition of the third liquid (Fig. 1). Thus WAGER and DEER [1939] write: "The Fe_2O_3 in the layered rocks up to the middle gabbro is present partly in the pyroxene and partly in iron ore which occurs as an interprecipitate mineral only. During this period, that is, while about 75 pct of the magma was solidifying, the amount of Fe_2O_3 precipitated was a little less than in the magma and the amount in the magma rose slowly until it attained about 3.5 pct. At this stage, when the middle gabbros were forming, magnetite appears as a primary precipitate."

The amount of Fe_2O_3 in the magma of Izu and Hakone had already attained to about 3.5 pct in the early stage of crystallization. Chemical compositions of porphyritic olivines, pyroxenes, and titaniferous magnetite in the rocks of Izu and Hakone were determined by chemical analyses and optical measurements, and their relative proportions in the rocks were estimated by volumetry. The result shows that during the early stage of crystallization of the pigeonitic rock series the ratio MgO to total iron (in wt) in the separating minerals (olivine and pyroxenes) ranges from 73:27 to about 50:50. However, during the middle to later stages of crystallization when magnetite separates together with the silicate minerals, the ratio is from 44:56 to 28:72. If this ratio is compared with that of the successive liquids as shown in Figure 1, it is readily seen that the difference of this ratio between the liquids and the separating minerals was great in the early stage but small or almost negligible in the middle to later stages. Therefore, the successive enrichment of iron in the liquid relative to MgO took place more markedly in the early stage than in the middle to later stages.

In the Skaergaard liquids, the enrichment of iron took place nearly constantly throughout the whole stage of crystallization except in the latest stage when 95 pct of the original liquid had solidified.

Table 1--Compositions of the original magmas of the Skaergaard intrusion and the pigeonitic rock series of Izu and Hakone and the average compositions of the lavas of the Hakone volcano; all recalculated as water-free

Constituent	A	B	C	D	Norm	A	B	C	D
	pct	pct	pct	pct		pct	pct	pct	pct
SiO_2	48.38	48.73	57.84	68.11	Q	-	1.86	14.76	29.76
Al_2O_3	19.04	16.53	16.35	15.01	Or	1.11	1.11	5.00	6.12
Fe_2O_3	1.19	3.37	2.45	1.69	Ab	20.96	9.96	22.01	30.92
FeO	8.74	8.44	6.81	3.39	An	40.03	39.20	30.58	21.41
MgO	7.90	8.24	3.35	1.13	Wo	4.87	8.70	4.52	0.93
CaO	10.56	12.25	8.48	4.93	En	10.20	20.60	8.40	2.80
Na_2O	2.46	1.21	2.60	3.63	Fs	6.73	12.14	9.11	3.83
K_2O	0.18	0.23	0.82	1.02	Fo	6.72	....	....	....
TiO_2	1.36	0.63	0.96	0.74	Fa	4.69	....	....	....
P_2O_5	0.07	0.10	0.14	0.20	Mt	1.86	4.87	3.71	2.55
MnO	0.10	0.29	0.20	0.14	Il	2.58	1.22	1.82	1.37
					Ap	0.34	0.34	0.34	0.34
Total	99.98	100.02	100.00	99.99					

A--The original magma of the Skaergaard intrusion. Average of two olivine gabbros of the chilled marginal facies [WAGER and DEER, 1939].

B--The original magma of the pigeonitic rock series. Average of two olivine basalts (nearly non-porphyritic) of the Hata basalt group (Pliocene), west of Atami, Izu Peninsula.

C--Average of 17 Old Somma lavas (the pigeonitic rock series).

D--Average of six Young Somma lavas (the pigeonitic rock series).

This difference in the rate of enrichment of iron in the Japanese magma combined with the high degree of fractionation in the feldspar series controlled the trend of its differentiation. Thus, in the early stage of differentiation, absolute enrichment of iron took place together with a slight enrichment of alkalies. In the middle stage, when the liquids attained to compositions represented by points close to that of the second liquid of Skaergaard (Fig. 1), the rate of enrichment of iron was suddenly reduced while the enrichment of alkalies continued at the same rate, so that the liquids began to become salic instead of becoming ferriferous.

The nearly straight-line variation of the hypersthenic rock series is explained as due to a mixing of the primary magma and the granitic material, the two having the compositions lying at the ends of the zone of variation. The effect of fractional crystallization attending the assimilation of foreign substance cannot be ignored.

It is interesting to note that almost the same conclusion was reached by TILLEY [1950] independently. He writes that most of the volcanic rocks occurring in orogenic belts were formed by contamination, but that the rocks of Izu and Hakone (southern part of the Huzi volcanic zone) are one of the rare examples which were formed from tholeiitic magma by fractional crystallization. The data used by Tilley include both the pigeonitic and hypersthenic rock series, but the rocks of the former series are far more abundant. The writer showed elsewhere [KUNO, 1952] that the pigeonitic rock series occurs in the area with a thinner granitic crust whereas the hypersthenic rock series occurs in the area with a thicker granitic crust. This fact indicates that the hypersthenic rock series represent the rock suite typical of the orogenic belts. This also agrees with Tilley's generalization.

In the succeeding discussions, the compositions of both the porphyritic and non-porphyritic rocks are used because it was found that if the composition of a porphyritic rock is plotted in the triangular diagram the point is not so much displaced from that of the calculated composition of its groundmass.

Calderas of the Hakone Volcano--The Hakone Volcano (Fig. 2) was built up by the eruption which took place in three different periods separated by periods of caldera formation [KUNO, 1950a].

The oldest cone was constructed by alternate eruption of lavas and pyroclastic rocks which are designated as Old Somma lavas. The top of this cone was probably about 2700 m high from its base. More than 30 successive layers of lavas are recognized in a single cliff section, amounting to an aggregate thickness of about 700 m. The rocks are mostly basalt and pyroxene

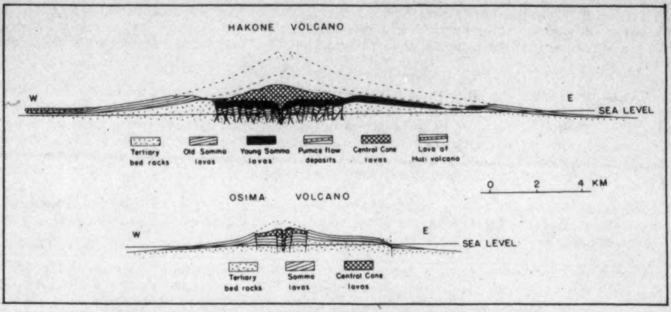
HAKONE VOLCANO
W
E
SEA LEVEL
Tertiary bed rocks
Old Somma lavas
Young Somma lavas
Pumice flow deposits
Central Cone lavas
Lava of Huzi volcano
0 2 4 KM
OSIMA VOLCANO
W
E
SEA LEVEL
Tertiary bed rocks
Somma lavas
Central Cone lavas

Fig. 2--Central cross sections of the Hakone and Osima volcanoes; the horizontal and vertical scales are the same

andesite of the pigeonitic rock series. Small quantities of dacite of the same series and andesite to dacite of the hypersthenic rock series were also erupted in the later stage of this period of activity. All available analyses of the rocks of the Old Somma lavas are plotted in Figure 3. The points are included in the area surrounded by the line marked OS.

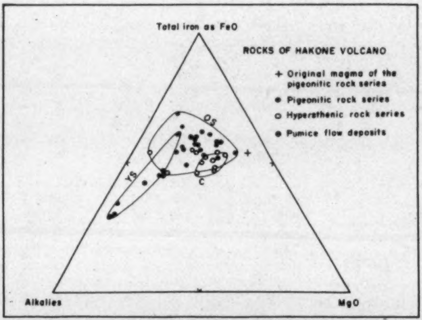

Fig. 3--Trend of variation of the rocks of the Hakone Volcano; OS - Old Somma lavas, YS- Young Somma lavas, C - Central Cone lavas

This period was followed by the subsidence of the top of the cone, resulting in a caldera about ten by six kilometers in diameter (referred to here as older caldera). This was succeeded by a long period of erosion during which the bottom of the caldera was greatly enlarged toward the east where the thick pile of the Old Somma lavas was completely removed to expose the Tertiary bed rocks (Fig. 2). As inferred from this degree of erosion and also from the fact that the whole history of the volcano occupied nearly half of the Pleistocene [KUNO, 1950a], the period of erosion lasted probably for a few hundred thousand years.

The next activity built up a gently sloped shield volcano within the caldera. This volcano consists almost exclusively of fluidal lava flows which are designated as Young Somma lavas. At least seven successive flows are recognized, attaining to about 300 m in aggregate thickness. The rocks are acidic andesite and dacite of the pigeonitic rock series, having compositions represented by points within the area marked YS in Figure 3. They all represent the advanced stage of differentiation of the pigeonitic rock series. It follows then that the magma which supplied the bulk of the Old Somma lavas continued further differentiation during the long erosional period after the subsidence of the caldera, and finally attained to the composition of the Young Somma lavas.

Immediately after the effusion of the Young Somma lavas, a great quantity of pumice was extruded from the crater in the form of pumice flows. The pumice consists of augite-hypersthene andesite and dacite, being quite heterogeneous in composition. Because of the glassy groundmass, we cannot tell whether the rocks belong to the pigeonitic or hypersthenic rock series. The two analyses of the pumice plotted in Figure 3 show that the compositions lie near the boundary between those of the Old Somma lavas and Young Somma lavas.

The extrusion of pumice was followed by the collapse of the center of the shield volcano to form a caldera (referred to here as younger caldera) having a dimension nearly equal to that of the older one.

After a short period of erosion, the third activity took place within the caldera; six lava domes and one steep-sided stratovolcano were formed. They are made up of viscous lavas (Central Cone lavas) of augite-hypersthene andesite, all belonging to the hypersthenic rock series. The lavas are quite uniform in appearance. The compositions of the rocks are represented by points lying within the area marked C in Figure 3. The location of these points indicates that the Central Cone lavas were originated through contamination of a primary basaltic magma by granitic material. Microscopical examination also shows that they captured xenocrysts of sodic plagioclase from foreign rocks. Olivine phenocrysts in all of these lavas contain picotite inclusions which are very rare in those of the rocks of the pigeonitic rock series of the Old Somma lavas. This indicates that the contamination took place in the earliest stage of crystallization of a primary magma more magnesian than any of the Old Somma lavas.

It may be concluded that, after the formation of the younger caldera, the primary magma rose up again from below and filled the magma reservoir, and assimilated the granitic material which lined the roof of the reservoir.

The volumes of the material erupted in different periods of activity were calculated by drawing a series of cross sections traversing the volcano. The result is shown in Table 2.

Table 2--Volumes of materials erupted in different periods of activity of the Hakone Volcano

Old Somma lavas	Young Somma lavas	Pumice flow deposits	Central Cone lavas
km^3	km^3	km^3	km^3
130	14	14	10

Note--The figures include volumes of the open spaces such as the gas pores of vesicular lavas and pumice. In pumice-flow deposits, it also includes the volume of the lithic fragments.

About ten per cent of the Old Somma lavas belong to the hypersthenic rock series, and the remainder contains phenocrysts averaging 20 pct of the rock. Therefore, the volume of the liquid magma erupted to form the pigeonitic rock series of the Old Somma lavas would be 94 km^3. The Young Somma lavas contain phenocrysts averaging ten per cent, so that the volume of the liquid magma erupted to form the lavas would be 13 km^3. Therefore, the ratio between the volumes of the liquid magmas erupted to form these two groups of lavas would be about 7:1.

The average compositions of the rocks of the pigeonitic rock series of the Old Somma lavas and Young Somma lavas were calculated from the analyses plotted in Figure 3, with the results given in Table 1, Col. C and D. These figures give only a rough picture of the average compositions of the liquid magmas existing in the reservoir during the two different periods of activity because the analyses incorporated in the calculation cover a wide range of compositions and some of them are those of porphyritic rocks.

The compositions and amounts of crystalline materials which are necessary to subtract from the original magma (Table 1, Col. B, shown by a cross in Fig. 3) to produce the liquids of compositions C and D were also calculated. Reasonable composition can be obtained for the crystalline material to be subtracted to form the liquid C if its amount is from 65 to 75 pct of the original magma. The most probable composition of the material is shown in Table 3, Col. E, its amount being 70 pct of the original magma. Reasonable composition can be obtained for the crystalline material to be subtracted to form the liquid D if its amount is from 85 to 90 pct. The most probable composition of the material, amounting to 90 pct of the original magma, is given in Table 3, Col. F. It follows then that the amounts of the liquid magmas left after the subtraction of these materials are 30 and ten per cent of that of the original magma. Actually, however, a part of the magma was removed from the reservoir to form the Old Somma lavas. Therefore, the amount of the magma available at the time of the eruption of the Young Somma lavas would be less than ten per cent. It may be concluded that the ratio between the amounts of the magma existing within the reservoir during the periods of eruption of the Old Somma lavas and Young Somma lavas would be larger than 3:1. This figure roughly corresponds to the ratio between the actual volumes of the erupted materials.

Table 3--Compositions of crystalline materials to be subtracted from the original magma to produce the average Old Somma lavas and Young Somma lavas

Constituent	E	F	Mineral	E	F
	pct	pct		pct	pct
SiO_2	44.9	46.7	Plagioclase	47.8	49.6
Al_2O_3	16.6	16.7		$(An_{88}Ab_{12})$	$(An_{82}Ab_{17}Or_1)$
Fe_2O_3	3.7	3.5			
FeO(+MnO)	9.5	9.3	Augite	23.8	22.5
MgO	10.3	9.0		$(Wo_{44}En_{40}Fs_{16})$	$(Wo_{42}En_{41}Fs_{17})$
CaO	13.8	13.1			
Na_2O	0.6	0.9	Hypersthene	10.9	17.6
K_2O	0.0	0.1		$(En_{66}Fs_{34})$	$(En_{66}Fs_{34})$
TiO_2	0.5	0.6			
			Olivine	11.2	3.7
Total	99.9	99.9		$(Fo_{75}Fa_{25})$	$(Fo_{75}Fa_{25})$
			Magnetite plus Ilmenite	6.3	6.3

Note--Compositions of the minerals are expressed in mol. per cent.

E--Crystalline material to be subtracted from the original magma to produce the average Old Somma lavas.

F--Crystalline material to be subtracted from the original magma to produce the average Young Somma lavas.

It is probable that even after the eruption of the Young Somma lavas there remained some liquid at the top of the reservoir together with liquid, possibly more basic in composition, which was trapped in the interstices of crystal mesh lying in the lower level. Volatile substances were concentrated at this stage. The liquids, crystals, and volatile substances were stirred to form heterogeneous magma charged with crystals and bubbles, and were erupted with an explosive violence resulting in pumice flows. The volume of the deposits of pumice flows shown in Table 2 includes that of lithic fragments (ten per cent), phenocrysts (15 pct), and gas pores (40 pct). If these volumes are subtracted from the total volume we can obtain the volume of the true liquid which is five cubic kilometers or only about five per cent of the volume of the liquid magma erupted to form the pigeonitic rock series of the Old Somma lavas.

Towada Caldera--The geology of this double caldera was described by TOMITA [1929] and KAWANO [1939]. Recent study by Soma and the writer confirmed that the results obtained by the previous investigators are correct as regards the general structure of the caldera.

In the first stage of activity, lavas and pyroclastic rocks of basic to intermediate pyroxene andesite were erupted. The aggregate thickness of this material is about 300 m. The last phase of this activity was an eruption of pumice flows, at least in two separate periods. The pumice consists of augite-hypersthene dacite and pyroxene-hornblende dacite. Owing to the irregularity of the topography of the surrounding area, the pumice flow deposits show a haphazard distribution which renders it difficult to estimate their total volume.

After this eruption the caldera measuring about ten kilometers in diameter and 500 m in depth was formed.

The next activity took place in the southeastern part of the caldera where a small cone made up of thin lavas, tuff breccia, and agglutinate of pyroxene andesite was formed, covering about half of the area of the caldera bottom. This activity was closed by an eruption of a small quantity of pumice which deposited on the flank of the cone and also outside the caldera in the form of pumice fall. Somewhere near the crater, the base of this deposit forms welded tuff. The pumice consists of augite-hypersthene andesite which is a little more basic than the material of the pumice flows.

After this eruption, a caldera measuring three kilometers in diameter and 400 m in depth was formed at the center of the cone. The old and young calderas are now filled with water and the flank of the cone is preserved as two peninsulas projecting into the lake.

The last activity was a formation of two lava domes of acidic augite-hypersthene andesite, one on the margin of the young caldera and another near the center of the old caldera.

According to the petrological study of the writer, all of the lavas erupted during the first and second periods of activity belong to the pigeonitic rock series. Chemical analyses by KAWANO [1939] also show that they are very close in composition to the rocks of the same series of the Hakone Volcano. The rocks of the lava domes belong to the hypersthenic rock series.

Caldera of the Osima Volcano--Osima is an island situated about 100 km SSW of Tokyo. The geology of the volcano was described by TSUBOI [1920] and chemical analyses of the lavas were published by several authors. The following discussion is based on the results of the studies of these authors and also on the writer's field work and petrological study.

The main part of the island consists of a stratovolcano of olivine basalt and olivine-pyroxene basalt. The material constituting this volcano is called Somma lavas (Fig.2). The caldera measuring four by two kilometers was formed at the top of the cone. The subsidence took place a few thousand years ago because remains of Neolithic men of the "Middle Jomon" and somewhat younger ages were found between younger flows of the Somma lavas [TORII, 1902]. The age of the "Middle Jomon" was determined by the radiocarbon method [LIBBY, 1951] as 4500 years old.

The post-caldera activity built up a small cone inside the caldera (Fig. 2). This cone is still growing; the last extrusion of lava took place in 1951. The lava of 1778 overflowed the caldera wall, veneered the flank of the main cone, and reached the sea. The post-caldera lavas or Central Cone lavas are augite-hypersthene basalt and hypersthene basalt entirely free from olivine.

Most of the Somma lavas and all of the Central Cone lavas belong to the pigeonitic rock series. The Somma lavas are either nonporphyritic or sparsely porphyritic and apparently uniform in composition, although a few porphyritic types are also known [TSUBOI, 1920]. The analyses of the Somma lavas are represented by points lying in a small area marked S in Figure 4, and their average composition is given in Table 4, Col. G. Some of the Central Cone lavas are sparsely porphyritic but others are porphyritic with phenocrysts up to 20 pct. The compositions of the sparsely porphyritic rocks are plotted in Figure 4 (points lying in the area marked C) and their average is given in Table 4, Col. H.

As seen from Figure 4 and Table 4, the compositions of the Central Cone lavas represent only a little advanced stage of differentiation of the Somma lavas. The differentiation could not have advanced so far by the time of the post-caldera eruption probably because of the short time interval between the two periods of activity.

When the average compositions are compared with the composition of the original magma (Table 1, Col. B), it is found that absolute enrichment of iron took place during the differentiation as in the Skaergaard intrusion [WAGER and DEER, 1939].

The most probable compositions of crystalline materials necessary to subtract from the original magma to produce the average Somma lavas and Central Cone lavas were calculated, with the result shown in Table 5. The amount of the material of the composition I to be subtracted is 45 pct of the original magma, whereas the amount of the material J is 50 pct. In other words, the amount of the liquid existing within the magma reservoir at the time of the eruption of the Somma lavas was 55 pct of the original magma, whereas the amount of the liquid now existing to form the Central Cone lavas is 50 pct, the ratio between the two being 1.1:1.

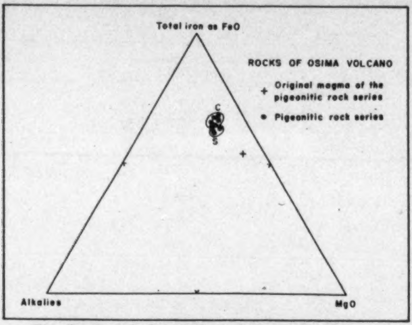

Fig. 4--Trend of variation of the rocks of the Osima Volcano; S - Somma lavas, C - Central Cone lavas

Table 4--Average compositions of the basalts of the Osima Volcano; all recalculated as water-free

Constituent	G	H	Norm	G	H
	pct	pct		pct	pct
SiO_2	52.52	52.59	Q	8.04	10.26
Al_2O_3	15.14	15.05	Or	2.22	2.22
Fe_2O_3	3.79	3.28	Ab	17.29	14.15
FeO	9.62	10.61	An	30.86	32.53
MgO	5.11	4.67	Wo	7.66	6.84
CaO	10.10	9.99	En	12.80	11.70
Na_2O	2.03	1.65	Fs	13.60	14.52
K_2O	0.43	0.40	Mt	5.57	4.87
TiO_2	0.83	1.41	Il	1.52	2.74
P_2O_5	0.15	0.20	Ap	0.34	0.34
MnO	0.30	0.16			
Total	100.03	100.01			

G--Average of three olivine basalts (sparsely porphyritic) of the Somma lavas

H--Average of six pyroxene basalts (sparsely porphyritic) of the Central Cone lavas

Actually, however, a part of the magma was removed from the reservoir to form the Somma lavas. Therefore, the amount of the liquid now existing would be less than 50 pct and the ratio somewhat larger than 1.1:1.

The actual volumes of the materials erupted were calculated from a series of profile sections cutting the volcano. The total volume of the Somma lavas is 19 km^3, and that of the Central Cone lavas three cubic kilometers. The latter figure could be changed to five cubic kilometers if the volume of the mass subsided to form the caldera would be twice the volume assumed for the above calculation (2 km^3).

The calculation of the volume of the Somma lavas is based on two assumptions: (1) the volcano lies on up-domed Tertiary bed rocks including those exposed at the northern margin of the island (Fig. 2); (2) the outer limit of the extension of the lavas is not far from the present coast line (Fig. 2). The up-doming of the bed rocks is a quite common feature in the dissected volcanoes of Hakone and Izu Peninsula. The gentle slope of the northern and southern skirts of the Osima Volcano indicates that the lavas do not extend into the sea far from the present coast line. From the analogy with the observed thickness of the material in the dissected basaltic

Table 5--Compositions of crystalline materials to be subtracted from the original magma to produce the average Somma lavas and Central Cone lavas of the Osima Volcano

Constituent	I	J	Mineral	I	J
	pct	pct		pct	pct
SiO_2	44.1	44.9	Plagioclase	50.2	52.2
Al_2O_3	18.2	18.0		($An_{97}Ab_3$)	($An_{86}Ab_{14}$)
Fe_2O_3	2.9	3.5			
FeO(+MnO)	7.3	6.7	Diopside	21.0	22.1
MgO	12.1	11.8		($Wo_{47}En_{45}Fs_8$)	($Wo_{48}En_{45}Fs_7$)
CaO	14.9	14.5			
Na_2O	0.2	0.8	Hypersthene	7.7	2.8
K_2O	0.0	0.1		($En_{70}Fs_{30}$)	($En_{68}Fs_{32}$)
TiO_2	0.4	0.0			
			Olivine	16.0	18.1
Total	100.1	100.3		($Fo_{80}Fa_{20}$)	($Fo_{80}Fa_{20}$)
			Magnetite plus Ilmenite	4.9	5.1

Note--Compositions of the minerals are expressed in mol. per cent.

I--Crystalline material to be subtracted from the original magma to produce the average Somma lavas.

J--Crystalline material to be subtracted from the original magma to produce the average Central Cone lavas.

volcanoes of Izu Peninsula, the maximum thickness of the Somma lavas of Osima is estimated as 400 m, as shown in Figure 2.

The estimated volume of the Somma lavas gives probably the minimum value, but it could not be twice as large. It follows then that the possible limits of the ratio between the volumes of the Somma lavas and the Central Cone lavas are 4:1 and 13:1, the most probable figure being 6:1.

This calculation shows that the volume of the magma which has previously been erupted as the Central Cone lavas is too small as compared with that of the magma which might be expected as remaining in the reservoir. The Central Cone or Mihara-yama would grow up until its volume would attain two or three times the present volume.

The geomagnetic study of the 1950-1951 eruption of the volcano strongly indicates that a large quantity of the magma is still existing in the reservoir. Thus RIKITAKE [1951] found that a spherical mass lying five kilometers below the caldera bottom and having a diameter of four kilometers (corresponding approximately to the diameter of the caldera) was heated above 600° C (the Curie point of magnetite) during the eruption. This may be interpreted that this mass was filled up by the magma having the temperature about 1200° C, the maximum observed temperature of the lava erupted. Instead of being spherical, the mass may be actually a cylindrical mass extending downward because both models would give nearly the same result on the geomagnetic observation on the surface. Even if we assume the spherical mass, its volume is 33.5 km^3. The total volume of the lava erupted during this period is about 0.034 km^3 [MURAUCHI, 1951], being only 0.1 pct of the volume of the magma in the spherical mass.

Caldera of Crater Lake--One of the best-studied calderas of Krakatau type is Crater Lake. According to the description by WILLIAMS [1942], the main cone formed by the pre-caldera eruption is Mt. Mazama which is largely made up of hypersthene andesite. At a slightly later period, lava domes of pyroxene-hornblende dacite rose up from vents arranged on an arcuate fissure on the northern slope of the cone. After the eruption of a tremendous amount of pumice and scoria of pyroxene-hornblende dacite and andesite, the top of Mt. Mazama collapsed to form the caldera. The post-caldera eruption built up a small cone of hypersthene-augite andesite near the margin of the caldera (Wizard Island).

According to the petrographic description and chemical analyses given by Williams, most of the lavas of this volcano appear to belong to the hypersthenic rock series. Probably the original magma which gave rise to the eruption of Mt. Mazama was already contaminated by sialic material. The post-caldera lava contains partially dissolved feldspathic inclusions probably derived from diorite or gabbro. Some of them are completely melted and drawn out to form streaks [WILLIAMS, 1942].

Calderas of the Hawaiian volcanoes--The geology and petrology of the Hawaiian volcanoes were studied by STEARNS [1946] and MACDONALD [1949].

According to these authors, the main body or primitive shield of the Hawaiian volcano consists of primitive olivine basalt together with a small proportion of picrite-basalt of oceanite type. After the caldera was formed at the top of the shield, the volcano still continued eruption of lavas having compositions either unchanged from those of the pre-caldera lavas or slightly changed to those representing the later stage of differentiation (olivine-poor basalt, basaltic andesite, and trachyte, such as those of the middle member of the Waianae volcano in Oahu). These post-caldera lavas are associated occasionally with picrite-basalt of ankaramite type which was formed through contamination of calcareous sediments [MACDONALD, 1949]. In the later stage of the post-caldera activity, the volcano was veneered by a series of lavas representing much advanced stages of differentiation, namely, andesine andesite, oligoclase andesite, and trachyte.

Thus the volcanic history and magmatic evolution of the Hawaiian calderas are quite similar to those of the calderas of the second type in Japan. The post-caldera lavas of Hawaii represent generally more advanced stages of differentiation than the pre-caldera lavas. However, as the bulk composition of the post-caldera lavas is not so much differentiated from that of the pre-caldera lavas, the volume of the liquid magma existing within the reservoir during the post-caldera eruption was enough to supply the lavas which entirely filled up the caldera and also covered the greater part of the primitive shield, without forming cone-in-cone structure as seen in the Hakone Volcano.

As pointed out by TILLEY [1950] and also confirmed by the writer's microscopical observation, there are two types of olivine basalt in Hawaii. One is tholeiitic or calcic olivine basalt characteristic of the recent lavas of Mauna Loa and Kilauea, and the other alkaline olivine basalt which apparently covers the surface of the primitive shields of other volcanoes such as Hualalai and Waianae. However, it is not yet certain whether these lavas of alkaline olivine basalt are underlain by greater amounts of lavas of calcic olivine basalt, as supposed by Tilley, or the two types of lavas interfinger with one another. The foregoing discussion is concerned with the volcanoes in which the main trend of differentiation may be considered as proceeding from calcic olivine basalt passing andesine and oligoclase andesites, to trachyte.

Calderas of Mull--The history of this famous island is much more complicated than those of the volcanoes described in the foregoing because there were more than one cycle of igneous activity and there were many intrusive phases.

According to the authors of the Mull Memoir [BAILEY and Others, 1924], most of the rocks erupted before the formation of the calderas belong to the plateau magma type but some of them to the non-porphyritic central magma type. Among the rocks of the latter type, basalt of Staffa type was erupted earlier than the basalt of the plateau magma type. These pre-caldera lavas have compositions representing the least differentiated magmas as shown in Figure 5.

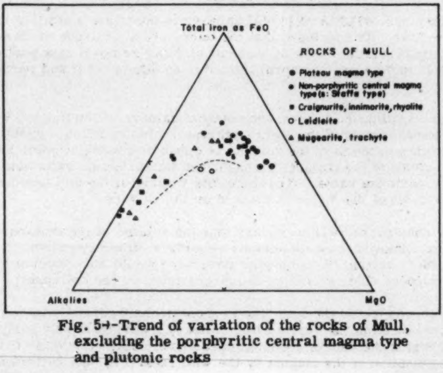

Fig. 5--Trend of variation of the rocks of Mull, excluding the porphyritic central magma type and plutonic rocks

The compositions of the lavas and minor intrusions of the post-caldera period cover the whole range of differentiation of the Mull magma series. Some of the lavas represent slightly advanced stages of differentiation of the non-porphyritic magma type and some of the sills, sheets, and dikes consist of andesite and rhyolite representing the late differentiates of the same magma type. From their mineralogical characters and chemical compositions (Fig. 5), it is evident that most of the basalt of the non-porphyritic magma type, andesite, and rhyolite correspond to the pigeonitic rock series of Japan and only a few of them (leidleite) to the hypersthenic rock series.

Thus the history and magmatic evolution of the Mull calderas agree generally with those of the calderas of the second type in Japan. The calderas of Mull are typical of those of Glencoe type of WILLIAMS [1941].

Mechanism of formation of calderas and magmatic evolution--The caldera of the Krakatau type may be interpreted as formed by a collapse along a complicated network of fissures which originates through shattering of the roof of the magma reservoir underlying the volcano by the explosive eruption of pumice. Many broken pieces of the roof are engulfed in the magma which is eventually contaminated by this material. This contaminated magma then extrudes to the surface to form the post-caldera cones or domes (Fig. 6).

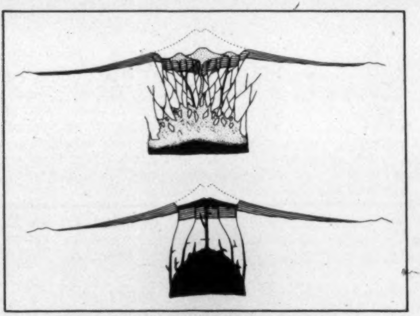

Fig. 6--Schematic profiles showing the modes of formation of the caldera of Krakatau type (above) and Glencoe type (below)

As seen from his drawings, WILLIAMS [1942] appears to postulate a similar mode of collapse for the caldera of Crater Lake. He concluded that the cause of the collapse of this caldera is a withdrawal of magmatic support from below as a result of rapid removal of a part of the magma from the reservoir largely in the form of lateral intrusion as dike swarm and partly in the form of pumice eruption.

The volume of the mass collapsed to form the younger caldera of the Hakone Volcano is estimated as 12 km^3. The actual volume of the solid material, including glass, crystals, and lithic fragments, of the pumice flow deposits of the volcano is estimated as eight cubic kilometers. Probably the estimated volume of the collapsed mass gives the minimum value and that of the pumice flow deposits the maximum value. Therefore, the volume of the collapsed mass cannot be accounted for by the volume of the material erupted on the surface.

However, the writer does not think it necessary that the volume of the collapsed mass equals the volume of the material removed from the magma reservoir either by extrusion to the surface or by lateral intrusion. Mere retreat of the magma downward would also account for the withdrawal of the magmatic support which should be the direct cause of the collapse.

The caldera of the second type or Glencoe type is most probably formed by a subsidence of a large block which is separated from the surrounding mass by a comparatively simple system of ring fissures. No shattering of the roof of the magma reservoir takes place, so that there is little opportunity of contamination of the magma by the wall rock (Fig. 6). Differentiation by fractional crystallization continued within the reservoir throughout the periods before and after the formation of the caldera. The post-caldera lavas therefore have compositions representing more advanced stages of differentiation than those of the pre-caldera lavas. The volume of the post-caldera lavas is roughly proportional to the volume of the magma existing in the reservoir which depends on the stage of differentiation attained by the magma. If the post-caldera eruption takes place at an advanced stage of differentiation, the volume of the magma available within the reservoir is so small that the erupted material builds up only a small cone within the caldera (for example, the cone formed after the subsidence of the older caldera of Hakone). If the post-caldera eruption takes place at a stage of differentiation only a little advanced from that at which the pre-caldera eruption took place, the volume of the magma in the reservoir is still enough to supply lavas which fill up the caldera and also cover the greater part of the pre-caldera volcano, obliterating entirely the former existence of the caldera (many of the Hawaiian shields).

In the Osima and Hawaiian volcanoes, the post-caldera eruption started immediately after the subsidence of the calderas, so that the magma had little time to differentiate. On the contrary, in the Hakone Volcano, the post-caldera eruption started at a time long after subsidence, so that the magma had enough time to attain to an advanced stage of differentiation.

According to Anderson [BAILEY and Others, 1924], the ring fissures of Mull are explained as formed by the release of pressure of the underlying magma. The ring fissures thus formed incline outward from the center of the ring. The calderas of Mull were formed by subsidence of the mass surrounded by the ring fissures.

Although WILLIAMS [1941] postulated a different mechanism for the formation of some Hawaiian calderas, MACDONALD [1945] showed that these calderas were formed by subsidence along ring fissures and therefore belong to the same category as the Mull calderas (Glencoe type).

BILLINGS [1945], on the other hand, discussed the mechanism of formation of caldera associated with ring dikes of New Hampshire. He concluded that the ring dikes made their way by piece meal stoping along zones of vertical ring fissures and that the subsidence of the cylindrical block surrounded by the ring dikes took place as a result of the outflow of part of the magma to the surface and also of the difference of specific gravity between the lighter magma and the heavier country rocks.

It is not yet known whether the ring fissures of the Hawaiian and Japanese calderas are vertical or incline outward. It has been shown that, in the calderas of the second type, contamination of the magma by the country rocks did not take place in an appreciable degree either before or after the subsidence. Most probably, therefore, these calderas were formed in the way postulated by Anderson [BAILEY and Others, 1924].

The ultimate cause of the subsidence and collapse of the calderas of the first and second types may be the withdrawal of magmatic support from below by the retreat of the magma downward and perhaps partly by its lateral intrusion. The essential difference between the two types lies in the mechanism of subsidence or collapse and the magmatic history depending on this mechanism.

Acknowledgments--The costs of the writer's field trips to the calderas of northern Honsyu and of the chemical analyses of the rocks of Hakone caldera, central Honsyu, were defrayed by the grants from the Japanese Government Expenditure for Scientific Research which are greatly appreciated by the writer. Nearly 100 new analyses have been made on the rocks of Hakone and adjacent areas by Kozo Nagashima, Morito Tiba, and Kenzi Nakata as a part of the project for the petrological and geochemical study of the Japanese volcanic rocks in which the writer as well as several other petrologists have been cooperating. The analyses were carried out in the Chemical Institute, Faculty of Science, Tokyo University, and also in the Chemical Laboratory of the Research Institute for Science and Technology of the same University, both directed by Kenjiro Kimura. The writer's thanks are due all of these. He also acknowledges the hospitality received from Dōwa Mining Co. during his trips to Towada caldera, north Honsyu, and the gifts of rock specimens from Toru Tomita of Kyusyu University which were collected by him during his survey of Towada caldera in 1928.

The writer wishes to take this opportunity of expressing his thanks to Takesi Minakami of the Earthquake Research Institute, Tokyo University, for helpful discussions on the activity of the Osima Volcano and to Gordon A. Macdonald of the Hawaiian Volcano Observatory for his guidance to the Hawaiian calderas and for critical discussions of the subject.

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REPORT OF THE SPECIAL COMMITTEE ON THE GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS, 1951-1952

George P. Woollard, Chairman

C. S. Beals	Ross Gunn	Howard Tatel
Francis Birch	H. W. Hemple	W. T. Thom, Jr.
Walter H. Bucher	Patrick M. Hurley	James T. Tilson
Maurice Ewing	Henry R. Joesting	J. Tuzo Wilson
R. A. Geyer	B. Perkins, Jr.	J. Lamar Worzel
	E. B. Roberts	

General remarks--In this report the Chairman will, insofar as practicable, quote the contributors who have done so much toward making the objectives of this Committee a reality. He is deeply indebted to all who so willingly contributed their time to prepare material for the report.

Since there have been several published reports covering activities of interest to this Committee at the IUGG meetings in Brussels, no account of those meetings will be included here. Nearly half of the Committee members were present, and it was gratifying to note the many informal conferences held outside of the scheduled sessions, for discussion of problems of direct interest to the Committee.

Gravity measurements and studies

U. S. Coast and Geodetic Survey (H. W. Hemple)--An areal gravity survey in western Tennessee and Kentucky has been completed and results will be published soon. This area of 46,000 sq mi includes 1500 stations with an average spacing of about six miles. Free-air and Bouguer anomalies have been computed on IBM punch-card equipment, and each system of anomalies contoured at five-milligal intervals.

The areal gravity survey of about 82,000 sq mi centered on Iowa was 40 pct completed when operations were suspended in December, 1951. The gravity party then made an areal survey of about 8500 sq mi in south-central New Mexico using an average six-mile spacing.

An extensive series of tests was carried out with the Brown pendulum apparatus at the Commerce gravity base. The magnetic effect on the period of the invar pendulums was determined by swings in fields ranging from -0.6 to +0.9 gauss. The maximum error from this source was of the order of one milligal for the magnetic fields normally encountered in field observations. For future work, Helmholtz coils have been constructed to produce a zero vertical component of the magnetic field around the pendulums. Tests were also made to improve flexure determinations at the Commerce base and to reduce effects of temperature variations by using heating coils on field set-ups. Observations conducted on piers at floor level in the gravity vault of the Commerce Building were much more reliable than were those made on piers extending some 30 inches above floor level. Unexplained differences of as much as ± 2 mgal were found between results obtained on the piers.

The Survey is cooperating with G. P. Woollard of the University of Wisconsin and the Woods Hole Oceanographic Institution, the Dominion Observatory of Canada, and the University of Toronto in the determination of a series of gravity bases from Mexico City to Fairbanks, Alaska. In accordance with plans formulated at a recent conference, observations with the Cambridge University multiple-pendulum apparatus will be made by personnel from the University of Toronto under sponsorship of the Dominion Observatory. The program for 1952 included determinations at about 15 stations from Mexico City to The Pas, Manitoba, and for 1953 the remainder of the chain to Fairbanks. In 1953, also, this Bureau will make measurements with the Brown apparatus from Great Falls, Montana, to Fairbanks. The combination of these two programs with previous measurements by G. P. Woollard with the Gulf (quartz) pendulums should enable the adoption of a uniform standard of calibration for all gravity-meter work in North America and possibly elsewhere.

In the summer of 1952 a coordinated gravity campaign for Alaska was initiated to establish a gravity datum by pendulum observations at Fairbanks, Anchorage, Nome, Point Barrow, and one or two other places. A network of secondary bases was established with a Worden gravity meter for coordinating future and existing regional surveys and furnishing control for detail surveys required by this Bureau for geodetic or geophysical purposes.

Further activities for 1953 will include completion of the areal survey in Iowa. In addition, the Coast and Geodetic Survey completed a free-air gravity-anomaly map of the south-central United States based on a compilation of gravity data supplied mainly by the oil industry. This map has ten-mgal contours which bring out very clearly all of the major anomalous masses related to the subsurface geology.

Dominion Observatory of Canada (C. S. Beals)--In 1951 about 2100 regional stations were established, chiefly over northeastern Ontario and western Quebec, and the southern portion of the Prairie Provinces. Three gravimeters, a Mott-Smith, a North American, and a Worden, were employed.

The preliminary gravity data for some 8000 stations will be published soon in four reports covering regional surveys in western Canada, southern Ontario, the Maritime Provinces, and for an extended region of the Canadian Shield in northern Manitoba and Ontario. Bouguer anomaly maps on a scale 20 mi to an inch are to accompany each report.

No pendulum determinations of gravity were made in Canada in 1951 or 1952. Plans are under way to continue pendulum work and extend the network of stations throughout central and northern Canada. A cooperative two-year program with the University of Toronto, using apparatus from Cambridge University, was started in the summer of 1952. The feasibility of rebuilding the bronze pendulum apparatus used for some years by the Dominion Observatory is being studied. It is expected that results can be greatly improved by modern methods of timing and precise temperature control.

Study of regional anomalies in the Canadian Shield has revealed large belt-like areas of alternating high and low gravity of the order of several hundred miles long and 50 mi wide. These have been interpreted as remnants of ancient mountain systems. A method has been developed for determining from gravity measurements the thickness of greenstone belts in Shield areas, and layers studied have shown depths of from four to six km.

A study of isostatic anomalies in areas close to centers of Pleistocene glaciation has indicated that compensation is practically complete and that there is little evidence to support the idea that the land is still rising following the removal of glacial loads.

In addition, the Dominion Observatory, plans to use the Cambridge pendulums in cooperation with the University of Toronto to occupy the line of pendulum bases being established between Mexico City and Fairbanks, Alaska, for calibration purposes.

U. S. Navy, Hydrographic Office and Office of Naval Research (ONR) (W. Kielhorn)--The writer visited G. P. Woollard at the University of Wisconsin to check the calibration of one of the high-range gravimeters of the Hydrographic Office and to secure experience in cold-weather observations preparatory to making a series of measurements on sea ice in the Arctic. Although no observations were secured off shore in the Arctic, a series of bases set earlier by the University of Wisconsin between Great Falls, Montana, and Point Barrow, Alaska, were successfully occupied.

Later R. C. Fitzpatrick of ONR, using the same instrument, reoccupied gravity bases set by the University of Wisconsin between Washington, D. C., and Kwajalein Island in the Pacific. Stations were established also on Eniwetok atoll.

U. S. Air Force Cambridge Research Center (J. A. Peoples, Jr.)--A. P. Crary and R. Cotell continued the gravity observational program initiated by Crary in Alaska in 1947. Observations were conducted on sea ice out to 400 mi from Barter Island and on the floating ice island T-3. Tie observations were made between Barter Island, and Fairbanks, Alaska, and Thule, Greenland.

Ohio State University Mapping and Charting Laboratory (W. Heiskanen)--The world-wide gravity program started in 1951, was endorsed by the International Union of Geodesy and Geophysics in Brussels by a resolution. The principal objectives are to convert the existing geodetic system to one world system, to check dimensions of the reference ellipsoid being used, to compute the undulations of the geoid and the deflections of the vertical, to control small-scale maps beginning from the scale 1:100,000, and to establish super-control points for long-range triangulations and Shoran measurements.

These studies will be conducted in the Mapping and Charting Research Laboratory of the Ohio State University under the supervision of W. Heiskanen. The Laboratory is glad to have as consultants Walter D. Lambert, G. P. Woollard, Maurice Ewing, and J. L. Worzel from the United States, F.A. Vening Meinesz from Holland, J. de Graaff Hunter from Great Britain, and P. Lejay from France, and as full-time associates R. A. Hirvonen from Finland and several younger scientists. Hirvonen has derived important formulas for computing the gravity-anomaly field at any altitude above the sea level when the sea-level anomalies are known.

The first phase of the world-wide gravity program will be to gather as much gravity material as possible and to study the most suitable methods for use in the routine work. Most countries, as well as leading oil companies, have promised active cooperation. Additional gravity measurements and continuously good international cooperation are prerequisites of the program.

The Isostatic Institute at Helsinki has continued publication of the reduction maps for helping the isostatic reductions of the gravity anomalies. In addition to maps of Europe already distributed, the Institute has recently published isostatic world maps giving the effect of the Hayford zones 10-1 not only for the Pratt-Hayford system but also for the Airy-Heiskanen system, the normal thickness of the Earth crust 20, 30, 40, and 60 km [E. NISKANEN and L. KIVIOJA Pub. 27, Isostatic Institute].

L. TANNI and E. NISKANEN [Pub. 25, Isostatic Institute] have tried to explain the reason for the large systematic one-sign gravity anomaly field.

W. A. Heiskanen spent the summer of 1952 in Europe accumulating unpublished gravity data

Columbia University, Lamont Geological Laboratory (J. L. Worzel)--With the assistance of Sven Saxon of the Geodetic Institute of Denmark, some 500 gravimeter observations made in the eastern United States with the high-range Frost gravimeter have been reduced and systematically indexed. These in large measure supplement the gravimeter network established by Woollard in this area and the pendulum observations of the U. S. Coast and Geodetic Survey. Approximately 100 of the observations are reoccupations of these earlier measurements.

Although the work at sea with the Vening Meinesz gravity pendulums in U. S. Navy submarines technically belongs in the report of the Committee for the Geophysical Study of the Ocean Basins, those measurements crossing the continental-shelf areas are of direct interest to this Committee.

Very steep gravity gradients indicated by the Bouguer gravity anomalies at the edge of the continental shelf on all traverses to date strongly support the seismic data showing a very real and sharp difference in crustal structure and composition at the boundaries of the continental blocks.

The pendulum gravity observations with the Gulf-Columbia quartz pendulum between Fairbanks, Alaska, and Mexico City made cooperatively with the University of Wisconsin are discussed under the program of that University.

Harvard University, Dunbar Physical Laboratory (Francis Birch)--P. Edward Byerly established 335 new gravimeter stations on traverses across the Sierra Nevada in the San Francisco-Coalinga region and secured additional gravity data for 200 more stations in the San Joaquin Valley region from oil company sources. Howard Oliver is working on a gravity study of the southern Sierra Nevada region. William Diment has extended the gravity study of R. J. Bean in Vermont, New Hampshire, and Massachusetts which was reported last year. This survey connects with that in southeastern Quebec being conducted by Michael Fitzpatrick. The gravitational relief is very pronounced with changes of as much as 60-80 mgal in distances of about 20 mi. These studies show in considerable detail the prolongation of the Green Mountain high through Vermont and Quebec.

Pennsylvania State College, Department of Earth Science (B. F. Howell, Jr.)--During 1951-52, one new gravity traverse was established from Tioga in north-central Pennsylvania to the New Jersey border with stations every 2 1/2 mi. There is a pronounced high (over ten mgal) near Tioga and a similar high in the Bradford, Pennsylvania, area. It is planned to determine the number of such highs in the northern Pennsylvania area.

University of Toronto, Department of Physics (J. Tuzo Wilson and George Garland)--The adjustment of the various series of measurements in the Maritime Provinces has been completed and iso-anomaly maps constructed. The interpretations fall into three general classifications: (a) anomalies due to density variations in pre-Carboniferous rocks (most striking are the effects of Devonian granites); (b) effects of deep Carboniferous basins; and (c) anomalies due to variations of density within the Carboniferous formations. An analysis of the last has indicated some interesting Mississippian salt structures. Bodies of salt appear to have been squeezed in along the axes of anticlinal folds, giving rise to long narrow gravity minima.

For the pendulum gravity program cooperative with the Dominion Observatory, Helmholtz coils have been constructed for the Cambridge pendulums to eliminate the effect of the Earth's magnetic field. On completion of test measurements between Ottawa and Toronto, a program was started to establish a new gravitational tie between Ottawa and Washington and make pendulum measurements along the calibration range between Mexico and Alaska begun in 1950 by Woollard.

In the study of the relationships between gravity anomalies and rock densities in the flat shield areas, Oldham has extended his measurements and found that the basement rocks have quite variable densities reflected in the gravity-anomaly values. Garland, however, has shown that the granitic areas of the shield are frequently characterized by large gravity minima of regional extent and that the areas of Precambrian sediments frequently are areas of gravity maxima. These anomalous relations have been intepreted as being due to variations in thickness of the outer granitic layer of the Earth's crust. The gravity minima are related to the "roots" of former Precambrian mountain ranges which persist to give an abnormal thickness for this layer, and the gravity maxima occur in the adjacent structurally low Precambrian basins where a more normal thickness of granitic crust exists.

Colorado School of Mines, Department of Geophysics (Ralph Holmer)--Iso-anomaly gravity maps are being constructed for Colorado based on a regional network of stations established by the writer, the observations of Woollard on his transcontinental traverse, and data from oil companies. The maps are being supplemented by regional magnetic-anomaly maps now being compiled.

Michigan College of Mining and Technology (Lloyal O. Bacon)--A regional gravity survey of upper Michigan has been completed following the level lines established by the U. S. Coast and Geodetic Survey. Observations were made at about four- to five-mile intervals with a Worden gravimeter. Results have been reduced to yield Bouguer anomalies. Detailed gravity surveys have also been carried out in connection with geologic studies of the iron deposits in the region.

University of Washington (J. W. Jones)--The regional gravity survey of Washington reported as started last year is still in progress. Fairly detailed studies of the large gravity minima associated with Puget Sound and an attempt to correlate seismic activity with the gravity anomalies have been made.

University of Wisconsin and Woods Hole Oceanographic Institution (George P. Woollard)--The series of global gravity measurements under the auspices of the Office of Naval Research included repeat observations of the world-circling loop of stations established in 1948 by Woollard. Measurements were carried out by W. E. Bonini, who also established new stations at Midway and Wake Islands; Formosa; Korea; Hong Kong; Hanoi, Saigon, and Hue in French Indo-China; Colombo in Ceylon; Madras, Hyderabad, and Bombay in India; Teheran in Iran; Bahrein Island, Kuwait, Bassara, Baghdad, Beirut, Damascus, and Tripoli in the Middle East; Nicosia in Crete; and Naples in Italy. Repeat ties were also effected by Bonini between Washington, D. C., Jacksonville, Florida, Trinidad, and Belen and Rio de Janerio in Brazil. W. A. Black established a series of gravity bases covering Mexico in cooperation with the Mexican government and the Inter American Geodetic Survey (IAGS) and extended the line of gravimeter bases connecting Great Falls, Montana, and Fairbanks, Alaska, to Toluca, Mexico. A basic network of gravity bases was also established in Costa Rica in cooperation with the local government and IAGS. The loop of global gravity measurements established earlier connecting Madison, Wisconsin, San Francisco, California, Hawaii, Johnson Island, Kwajalein, Guam, Japan, the Aleutian Islands, and Alaska was repeated. Another series of measurements completed in cooperation with the U. S. Weather Bureau and the Dominion Observatory of Canada included observations at the Arctic weather stations. Independent sets of observations were made by Black and an observer from the Dominion Observatory of Canada at Montreal, Churchill, Resolute Bay, Isachson, Mould Bay, Eureka, Alert, and Thule. These bases extending to 83° north latitude are shown in Figure 1. Repeat ties were also effected by Woollard and S. P. Worden of the Houston Technical Laboratories between New York and Teddington with two high-range Worden meters. Current work is centered in South America.

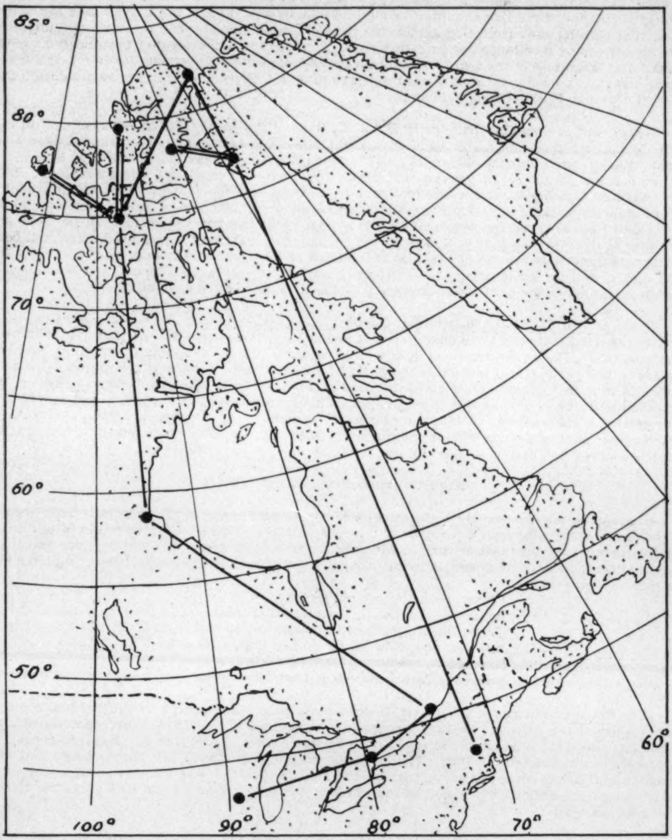

Fig. 1--Gravity bases at Arctic weather stations

In the United States one new gravity traverse was established between Wisconsin and Great Falls, Montana, with stations at about ten-mile intervals, and a regional network following the level lines of the U. S. Coast and Geodetic Survey in Wisconsin and the boundary portions of the adjacent states was completed. W. Hinze established several hundred gravity observations over the Baraboo syncline, and N. C. Harding established a similar number over the Meteor Crater area in Arizona. This last investigation suggests that there are three anomalous masses in the crater area. In the Mid-Continent region considerable additional work was done toward delineating further the exact boundaries and magnitude of the large gravity high running between Clay Center, Kansas, and Superior, Wisconsin. This high appears to follow the axis of the Lake Superior syncline in the Minnesota-Wisconsin area of exposed Precambrian rocks. In this respect it is similar to some of the features reported by Garland in Canada. It differs in that the geologic evidence shows that the inter-bedded lava flows now dipping toward the axis of the syncline were flowing away from this axis at the time of emplacement. The present structure therefore appears to be a collapse one probably resulting from the withdrawal of magmatic material at depth. The magnitude of the local anomaly (over 100-mgal relief) suggests further that ultrabasic material is locally present in what appears to be a fissure some ten km deep beneath the present cover of Precambrian sediments.

Wayne Ault of Columbia University and J. C. Rose of the University of Wisconsin, with the Gulf-Columbia compound quartz pendulums, established a series of gravity bases between Fairbanks, Alaska, and Cheyenne, Wyoming, and between Houston, Texas, and Tacubaya, Mexico. The Toluca volcano station set by gravimeter, which would have given an equivalent sea-level station for a location in South America, was lost because of failure of the auxiliary equipment at high altitudes. Rose is working on another pendulum apparatus using two sets of quartz pendulums loaned by the Gulf Research and Development Co. It is hoped that this new apparatus will be more portable than equipment used last year and permit higher accuracy in that four pendulums will be swung simultaneously instead of two. On completion of the apparatus it is planned to repeat the 1951 measurements and to occupy the stations between Corpus Christi, Texas, and Winnipeg, Canada, established for calibration purposes by the U. S. Coast and Geodetic Survey.

University of California, Institute of Geophysics (L. B. Slichter)--The tidal variations of gravity reported last year were observed at Los Angeles, Pasadena, Hawaii, and Attu, and have been analyzed. The terms produced by the yielding of the Earth (including the oceans) is characterized by two parameters, one expressing the time phase and the other the amplitude. At a single location the parameters were found to be constant in time. Geographically, however, the phase shifts differ greatly at widely separated stations. Knowledge of the phase and amplitude parameters, when constant, enables the classical harmonic tidal constituents to be easily computed. Comparisons of results by this simplified method with those by standard U. S. Coast and Geodetic Survey and British Admiralty methods show satisfactory agreement.

Magnetic measurements and studies

U. S. Geological Survey (H. R. Joesting)--Aeromagnetic maps of all of Indiana have been published, and a state-wide map and report are in preparation. Thirty thousand miles of aeromagnetic traverse covering most of northern Minnesota have been completed and the data are available in either published or open file form. Cross-country aeromagnetic profiles completed during the past year are as follows:

Provo, Utah--Portland, Oregon
Knoxville, Tennessee--Chicago, Illinois
Grand Island, Nebraska--Santa Fe, New Mexico
Albuquerque, New Mexico--Las Vegas, Nevada
Spokane, Washington--Bismarck, North Dakota
Stockton, California--Salt Lake City, Utah

U. S. Coast and Geodetic Survey (E. B. Roberts)--Magnetic surveys in Central and South America have been advanced through a cooperative program of repeat measurements conducted by the Inter-American Geodetic Survey. In the United States, a program of extensive repeat measurements is planned for 1953. The airborne magnetic survey of the United States and adjacent coastal areas being conducted in cooperation with the U. S. Air Force is well under way. Early calibration difficulties caused by magnetic disturbance arising from fittings in the aircraft have been overcome.

Dominion Observatory of Canada (C. S. Beals)--Magnetic surveys this past year were confined principally to the eastern part of Canada from the southern coasts of Newfoundland and Nova Scotia to the southern coast of Ellesmere Island. Measurements of declination, inclination, and total force were made at 43 repeat stations and 69 new stations. One party established 54 stations in and around the Labrador Trough area. In addition, a new total-force map of Canada was constructed.

Columbia University, Lamont Geological Laboratory (J. L. Worzel)--The total intensity was measured by E. Miller from a ship along various tracks from New Jersey to Cape Cod out to 30 mi offshore. The measurements were made with a continuously recording airborne magnetometer modified to be towed about 39 ft under water and 200 ft astern of the survey vessel. This work was carried out cooperatively with J. Ayers of Cornell University on a U. S. Coast and Geodetic Survey vessel. Several large anomalies were found, and in general the results correlate very well with existing magnetic knowledge based on shore and airborne magnetic surveys. More extensive work is planned to be carried out under a contract with the Office of Naval Research.

University of Wisconsin, Department of Geology (George P. Woollard)--A regional reconnaissance vertical-component survey of Wisconsin and adjacent areas has been nearly completed by D. Plouff and M. Johnston. Observations were made at the same sites occupied in establishing the regional gravity survey. The large and striking magnetic anomalies present can be correlated for the most part with gravity anomalies. More detailed work by J. Belshe in the Wassau area is part of a study of the petrologic variations of the crystalline rocks. Work was started in 1952 on the reduction of the vertical-component magnetic observations made in connection with the gravity reconnaissance survey of the Appalachian Mountain system between New York and Florida.

Seismic studies

U. S. Coast and Geodetic Survey (E. B. Roberts)--The earthquake-intensity studies reported last year have been extended to include determination of (1) a provisional absolute-intensity scale that to a limited extent assigns accelerations to any ground period that may be recorded in an earthquake of any intensity, (2) formulas for estimating ground motions at any distance from an earthquake of known or assumed intensity, taking only certain broad phases of geology into account, and (3) the similarity between earthquake spectrums and corresponding acceleration envelopes.

Based on information from a very complete survey of world-wide earthquakes, a map of earthquake epicenters for 1951 has been prepared (see Fig. 2).

New seismograph equipment was installed at Nelson, Nevada; Pierce Ferry, Arizona; Montana School of Mines, Butte, Montana; State University, Fayetteville, Arkansas; and, University of South Carolina, Columbia, South Carolina.

U. S. Geological Survey (H. R. Joesting)--Seismic, tilt, and ground-potential measurements are being made on Adak and Great Sitkin Islands in the Aleutians and at the Hawaiin Volcano Observatory as part of the long-term research program on volcanoes.

Dominion Observatory of Canada (C. S. Beals)--In view of the very active seismic characteristics of the Pacific Coast region of British Columbia, a full-time seismologist has been transferred to Victoria to study the seismicity of the region. Continued crustal studies in the Canadian Shield area indicate a single-layered crust with a depth of about 35 km and a compressional wave velocity of about 6.0 km sec.

Studies of microseisms at the new seismograph station at Resolute Bay, N.W.T., have indicated a good correlation with storms over the North Atlantic. Studies of the fault planes of earthquakes in the circum-Pacific area suggest that transverse faulting is the predominant type, an unexpected conclusion of considerable geophysical interest.

Columbia University, Lamont Geological Laboratory (J. L. Worzel)--Further study of the Lg phase of earthquakes, a short-period, large-amplitude surface shear wave propagated over continental paths only, indicates that the crust behaves as a remarkably homogeneous plate for transmission of waves of this length. The dispersion of Rayleigh waves R_3, R_4, and R_5 of period one to seven minutes recorded at Pasadena from the great earthquake of August 15, 1950 has been used to study mantle structure to a depth of 1500 km. Preliminary results indicate a very homogeneous structure independent of azimuth and continental or oceanic paths.

In the program of seismic work at sea conducted under auspices of the Office of Naval Research are two traverses across the Gulf of Maine and several stations established over the Grand Banks. Of particular interest is the fact that no typical granitic velocities (4.5-5.5 km/ sec) were obtained.

University of California, Department of Geological Sciences (Perry Byerly)--The determination of methods of computing the energy in all the groups of waves on seismograms from various stations is being actively pursued. For studying those peculiar Rayleigh and Love wave groups which travel with very slow velocities primarily through valley alluvium, it is planned to install a temporary seismic station at the edge of the San Joaquin Valley. J. C. DeBremaecker has completed his study on the amplitudes of P normal out to 20 degrees and finds, despite a large scatter, no evidence of a minimum in this region. Byerly plans to study the records of West Indian earthquakes from Ottawa south along the Atlantic Seaboard under a Guggenheim Foundation Fellowship.

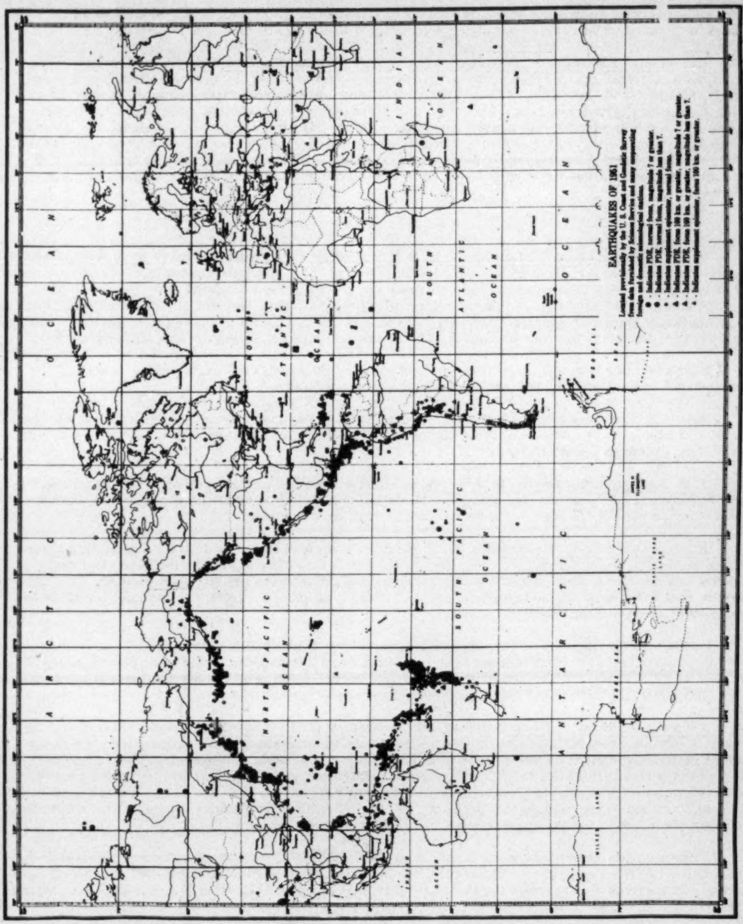
EARTHQUAKES OF 1951
ARCTIC OCEAN
NORTH ATLANTIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
NORTH PACIFIC OCEAN
SOUTH PACIFIC OCEAN
ANTARCTIC OCEAN

Fig. 2--Earthquakes of 1951

University of California, Institute of Geophysics (L. B. Slichter)--From studies of six large quarry blasts in the Wisconsin area, the preferred interpretations lead to depths of the Mohorovicic discontinuity of 40 to 44 km, with a thin superficial layer 0.6 to 2.8 km thick of wave velocity 4.2 to 4.5 km/ sec. In the major layer the velocity increases gradually from about 6.0 km/ sec at the top to 7.0 km/sec at the bottom. Below this layer the compressional wave velocity is about 8.17 km/sec.

Carnegie Institution of Washington, Department of Terrestrial Magnetism (Howard Tatel)--Work planned for 1953 includes repeat seismic observations on the eastern seaboard using large explosive charges fired by the U. S. Navy in Chesapeake Bay. The results obtained in Minnesota in 1951 are still being studied.

University of Wisconsin, Department of Geology (George P. Woollard)--In the summer of 1951, some 200 seismic depth measurements were made in south-central Wisconsin in connection with a study of the location of buried Precambrian ridges having over 1000 ft relief that existed as islands during much of early Paleozoic time. This program is being extended into eastern Wisconsin. A new program has been initiated for studies of the structure of the Lake Superior syncline. Under auspices of the Office of Naval Research, the seismic measurements across the Atlantic Coastal Plain from North Carolina to Florida are being resumed and coordinated with the offshore seismic traverses being established by Columbia University.

Massachusetts Institute of Technology (P. M. Hurley)--Studies are being conducted on the components of seismic response. Auto- and cross-correlation analysis of several seismograms from regions of known structure indicate that the response is made up largely of a predictable component that can be eliminated by a suitable linear operator, or predictor, leaving well-defined reflections which appear with greatly increased relative amplitude. This procedure allows reflections to be readily identified in places where they are known to exist but still are not interpretable from ordinary multiple-trace seismic records. The system not only improves the signal-to-noise ratio in the identification of pulse arrivals, but also constitutes a method of obtaining a better understanding of the filter-like characteristics of the ground.

Radioactive and thermal studies

Columbia University, Lamont Geological Laboratory (J. L. Kulp)--Three natural radiocarbon units are in operation for the measurement of geologic time. The method has been extended to 30,000 years, and several hundred measurements have been made. The rate of deep ocean circulation is being studied, with preliminary results suggesting that the turnover is on a scale of thousands of years. The origin of petroleum is also under investigation in cooperation with P. V. Smith of the Esso Development Laboratories. It appears that recent hydrocarbons are present in sufficient quantity to account for known petroleum. Radon leakage measurements from radioactive minerals show this to be an important factor in U-Pb age determination. It seems that radioactive minerals are amenable to helium age determination. A long-range program of developing the U-Pb method has been initiated. A new mass spectrometer nearly completed will be devoted entirely to this problem. Preliminary measurements show that lead tetramethyl and PbSO4 are more satisfactory than Pb12 in measuring the mass spectra of lead. Work continues on the strontium isotope method of dating carbonate rocks and fossils. Mass spectrometric precision of 0.2 pct has been attained and modern ocean strontium has a Sr^{8}/Sr^{86} ratio 1 pct higher than Silurian strontium. Radium measurements on deep-sea cores are being continued to investigate the ionium method of age determination. Helium age work is progressing, with particular emphasis on measuring up through the Pleistocene, using mass spectrometric techniques. A research program on the origin of native sulfur in salt domes has been initiated. The sulfur isotopic variation will play a major role.

Massachusetts Institute of Technology (P. M. Hurley)--The Cabot Spectrographic Laboratory under the direction of L. H. Ahrens is engaged in a broad study of the composition of the crust, and of chrondritic meteorites. It is hoped that from a knowledge of the relative abundances of all the elements it may be possible to reach some conclusions on the relationship between the mantle, the crust, and meteorites. Of particular interest from the point of view of energy and the history of the continents are the measurements of potassium in meteorites and ultramafic rocks. The potassium content of ultramafic rocks is much lower, by a factor of about 30, than has usually been assumed.

Work is continuing on the determination of helium ratios in various minerals and under various geological conditions. The purpose is to investigate the limiting factors controlling the reliability of helium ratios as a means of determining geologic age. The study of alpha-radiation damage and its effect on helium loss is continuing.

Preliminary results indicate that minerals differ widely in the rate at which the crystal structure recovers from alpha-particle damage. Work is also continuing on helium ratios in young or weakly active zircons.

In the study of Sr^{87}/Rb^{87} ratios, and the ratios of the stable isotopes of Sr, a number of samples of biotite and several samples of common strontium minerals have been studied in collaboration with L. T. Aldrich's laboratory at the Department of Terrestrial Magnetism. A variation in the stable 86/88 ratio was found, indicating that natural variations in the ratio of stable isotopes can be significant in this mass range. The 87 isotope showed some indication of varying in abundance with age of the minerals, but there were notable discrepancies.

In the study of the argon-potassium-ratio method, apparatus is being constructed for the absolute measurement of total argon in minerals. It is believed probable that all the argon in potassium-bearing minerals of granitic rocks is radiogenic, at least within the accuracy of measurement. This assumption can be tested by the present mass spectrometer without difficulty since A^{38} has become available from the Atomic Energy Commission. The apparatus consists essentially of furnaces which provide calcium or barium vapor for the removal of gases other than the noble gases.

Lead-uranium ratios in accessory zircon are still considered to afford one of the most promising methods of age determination. Work is being continued by M. K. Smith on improving the accuracy of spectrographic determinations of the Pb in zircon. It is agreed that this method will probably never be as accurate as desired for single age measurements on unknown rocks, but the combination of a spectrographic determination of Pb and a radiometric determination of U + Th is so much more feasible an operation for ordinary geological laboratories that it is considered worthwhile to explore the limits of this method.

Of basic importance to the possible use of helium or lead ratios in zircons and also to the study of the amount of energy stored in igneous rocks versus that liberated by radioactive decay, is the relationship between structural damage in zircons and total alpha dosage. H. W. Fairbairn and P. M. Hurley are studying the change of unit-cell dimensions and intensity of x-ray diffraction in samples of zircon that have suffered increasing amounts of alpha irradiation. The "annealing half-life" is found to be sufficiently long for zircon at ordinary temperatures so that only in the cases of the oldest minerals and the most radioactivity is there any approach to equilibrium between disordering and annealing. This is found not to be the case with sphene and apatite, in both of which the annealing rate is high enough so that the minerals exhibit very little disorder when this equilibrium is established.

Investigation has shown that radioactivity in zircon frequently exists as small inclusions of highly radioactive minerals giving a non-uniform disorder throughout the structure. This distribution gives rise to problems in the measurement of the radioactivity of the sample by some techniques and has resulted in quite a variation in analytical results of U + Th by alpha-counting methods. Knowledge of this fact is sufficient to induce investigators to use the right method of analysis, so that there should not be in the future the same discordance of results that has occurred to date. X-ray spectrometer records provide an easy way of examining the uniform or non-uniform distribution of uranium in the mineral.

Work is progressing on the measurement of total energy given out continuously by the radioactive disintegration of uranium, thorium, and potassium in basalts and diabase. Rocks of this type being studied are the Columbia plateau basalt, the diabase intrusives of the Canadian Shield area, and the Deccan plateau basalts of India. Other studies are being conducted concerning the amount of this energy going into heat and the amount being stored as disordering or chemical changes within the minerals of the rock.

At present it seems as if most of the energy is released immediately as heat, and that the heat production in these rocks is sufficient to raise a serious objection to the existence of a layer of basalt below the crust. The heat production by the rocks of the crust itself seems to be almost as great as the heat flux at the surface, leaving the heat flow into the base of the crust from the mantle at a low value.

Work is continuing on the measurement of thorium and radium with depth in two cores from the Sigsbee Deep in the Gulf of Mexico. Results indicated that radium was out of equilibrium with ionium in the top 100 cm of the first core, and suggested a deposition rate of about one cm per 100 years.

W. Z. Leavitt is continuing studies on the measurement of the diffusion coefficient of sodium in albite at temperatures below the melting point. The work clearly demonstrates that the movement of alkalis through the solid structure of the feldspar minerals is too small for geological significance in questions of large-scale granitization or other metamorphic processes. This statement refers only to the migration through the solid crystal structure and not around grain boundaries or along planes of weakness.

University of Toronto (J. Tuzo Wilson)--Slack and Whitman have confirmed their previous results and those of Keevil that radioactivity is zoned in batholiths.

Well over 100 new isotope lead age determinations have been made and are being published. Most relate to the Canadian Shield. From these measurements the following conclusions can be drawn: (a) The Shield may be divided into provinces, each with a distinct maximum age. Minerals from pegmatites are always among the oldest, but vein deposits commonly are of variable age up to the maximum. It is suspected that each province was only formed ab initio just before the time of pegmatite deposition and that the continents have grown outward from nuclei. (b) The nuclei in each continent for which there are data have pegmatites about 2400 million years old, and all the nuclei have rocks of the Keewatin greenstone type and lack pure quartzites and limestones.

Harvard University (Francis Birch)--W. H. Pinson, Jr., is working on the uranium content of rocks and meteorites as determined by a fluorimetric method. This method, while subject to difficulties of its own, by-passes the troubles of the alpha-counting methods. A large program is planned and results are beginning to accumulate.

Geological and tectonic studies

U. S. Geological Survey--The very comprehensive research program of this agency cannot be adequately summarized here, and rather than present a fragmentary picture it seems best to refer to the Annual Report of the Director, and to add that the report contains a great deal holding the Committee's interest.

U. S. Coast and Geodetic Survey (E. B. Roberts)--The program for repeating triangulation measurements across fault lines was continued in 1951. Preliminary results of surveys completed near Monterey Bay and northeast of San Luis Obispo, California, indicate a systematic movement in a northwesterly direction of the area on the southwest side of the fault during the past 20 years.

Johns Hopkins University, Department of Geology (Ernst Cloos)--Investigations are being conducted in areas where so-called normal Appalachian folds grade into asymmetrically overturned folds involving crystalline rocks to gain a better understanding of Appalachian folding. Work includes: (a) a structural analysis of the critical area of Sugarloaf Mountain, and (b) structural mapping of the Catoctin Mountain area, the upper limb of the South Mountain anticlinorium, and portions of the Blue Ridge. A study of the changes in metamorphism in Montgomery County across the crystalline belt between Washington, D. C., and Frederick Valley has been completed and will be published this year.

Illinois Geological Survey (M. M. Leighton)--The very broad and active research program of this survey can be subdivided into 24 subheads of which the following three are of particular interest to this committee: (a) stratigraphy of the Paleozic and Pleistocence systems in Illinois; (b) special studies of the subsurface stratigraphy of the Chester series, Lower Mississippian formations, Kinderhook New Albany strata, and Devonian system; and (c) structural studies.

A nearly completed revised structural map of the southern two-thirds of Illinois based on data from 1750 deep and numerous shallow wells is to be published this year.

Princeton University, Department of Geology (W. T. Thom, Jr.)--From cooperative team research in the Yellowstone-Bighorn region of Montana and Wyoming for several years, it appears that the deformational history of the region can be subdivided into seven phases since early Precambrian time. From the structural patterns the orogenic forces that were present can be defined in terms of direction and orders of stress magnitude.

The evidence suggests that the tectonic and igneous activity of the Laramide disturbance gave rise to four parallel deformational waves which shifted eastward by one wave length with each new phase of crustal disturbance. The zone of the first wave was featured by explosive volcanic eruption. The second zone 100 to 200 mi to the west was featured by laccolithic intrusions and more quiescent eruption. The third displaced another 100 to 200 mi westward was characterized by large-scale thrust faulting causing the elevation of linear mountain ranges. The fourth was one of batholithic intrusion which took place to the west (behind) the zone of thrust faulting. It seems fairly certain that subcrustal increases in temperature were a necessary preliminary in each region before there was any yielding to the compressional deformation, and that the formation of large-scale magmatic blisters within the outer crust were a necessary preliminary to any large-scale thrust faulting.

University of Toronto, Department of Physics (J. Tuzo Wilson)--The theory of conical failure in the Earth's outer shells as developed by Scheidegger has been applied to most of the major Earth's tectonic elements. The basic points of the theory are (a) a thin spherical shell must fold in a smaller pattern than a thick one if the core shrinks by the same amount; (b) the speed of cooling of a sphere decreases if some material generating radioactive heat moves toward or away from the center; (c) at the level of no strain of a cooling sphere the temperature depth curve must be essentially straight; (d) convection currents in the mantle would not result in removing more heat from the center than conduction alone. On this basis a contracting Earth with a cooling asthemosphere would cause sliding fractures giving surface tectonic patterns similar to those of the major orogenic belts of the Earth.

Consideration of present rates of erosion and vulcanism show that if geological events considered normal had occurred in the past at the same rate as now, the entire growth of the continents could occur during geological time.

Columbia University, Lamont Geological Laboratory (J. Northrup)--Continuous soundings on recording fathometers on the RV Atlantis and RV Caryn of the Woods Hole Oceanographic Institution in 1951-52 indicate numerous canyons debouching southward toward the Bahamas from the Blake Plateau off the South Carolina and Georgia coasts. In the Bahamas the canyons have a deep incised "V" in the center of the channel and tributary channels enter at grade. In the Gulf of Maine there are three separate basins all over 150 fathoms deep separated by 100-fathom divides, and off Nova Scotia cores indicate that the Triassic material observable in the Bay of Fundy continues out into the Gulf of Maine. On the edge of the Newfoundland Bank, canyons are more numerous than where the continental shelf is narrower to the south. These canyons continue out to at least 2200 fathoms. Cores taken in the "gully" southeast of Sable Island show alternate layers of sand and clay with some edgewise conglomerate.

Johns Hopkins University, Chesapeake Bay Institute (M. C. Powers)--Electron microscopy, x-ray analysis, diffraction, thermal analysis, and chemical methods are being applied to the study of the clay fraction of the sediments of the Patuxent Estuary, Chesapeake Bay, and the adjacent Continental Shelf. A study is in progress for determining the role played by the Mg++ and K+ in exchange reaction in marine sediments. In addition, cores are being taken and routine sedimentation analysis carried out. This work is being supported jointly by Maryland, Virginia, and the Office of Naval Research.

Ohio State University, Department of Natural Resources (H. Pincus)--A study of the sedimentary processes in and around Lake Erie includes mapping of the bottom topography, bottom sampling and coring, and the measurement of bottom currents. Mechanical, mineralogical, and carbonate analyses are being made. This work is sponsored by the Army Engineers and several departments of the State of Ohio.

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DISCUSSION OF

"SOME EFFECTS OF FIRE AND ASH ON THE INFILTRATION CAPACITY OF SOILS"

by R. H. BURGY and V. H. SCOTT

[Trans., v. 33, pp. 405-416, 1952]

Arthur F. Pillsbury (Department of Irrigation and Soils, University of California, Los Angeles, California)--The effect of brushland fires upon runoff and erosion has long been a subject of heated discussion. The authors are to be commended for obtaining these excellent data on the effects of burning upon the infiltration capacity of the soil. The writer has some fragmentary observations on this and related subjects, to wit:

UCLA brush-covered hillside--Plots on this hillside were burned in the spring and summer of 1942 in the hopes of developing techniques to simulate natural burns on plots. In the spring of 1943 some laboratory tests showed the structure of the burned plots to be at least as good as that of the adjacent unburned plots, and usually better. Average penetration of the winter's rainfall was 3.6 ft for the burned plots and 3.2 ft for the adjacent unburned plots. In a storm on January 21-22, 1943, there was evidence of more washing of ashes and soil from the burned plots than from the unburned plots.

Pauba Ranch natural burn--A brush-covered area on this ranch in southwestern Riverside County was burned over in the summer of 1942. There had been an average of about four inches of litter on the soil surface, and considerable half-decayed litter was mixed with the top few inches of soil. All such material, above and below the soil surface, was reduced to ash by the fire. The average relative infiltration rate of disturbed samples of surface soil was 10.4 in/hr for burned areas and 7.4 in/hr for adjacent unburned areas. The samples were obtained May 5, 1943, after the winter's rainfall. There were fresh fans of mixed ashes and soil materials at the bottom of each little draw below the burned areas, and none below the unburned areas.

Santa Rosa Ranch natural burns--In 1941-1942, I started establishing some runoff-erosion plots on the Santa Rosa Ranch in southwestern Riverside County. A natural burn occurred on part of this ranch on about January 3, 1943. On January 28, 1943, undistrubed cores of surface soil (2-inch diam., 1 1/2 inches deep) were obtained at the edge of the burned area (adjacent to subsequently established plot A1). Six samples were in the burn, and six were outside the burn. Soil and exposure appeared similar in all cases. The cores were wet, then placed on a desorption table, and the results shown in Table 1 were obtained.

Table 1--Data on moisture content

Area	Moisture content at 0 tension		Moisture content at 0.1 atmos. tension		Bulk density	
	Range	Average	Range	Average	Range	Average
	pct	pct	pct	pct	gm/cm^3	gm/cm^3
Burned	51.5-74.9	62.3	42.8-51.6	49.0	0.9-1.3	1.0
Unburned	45.2-57.1	51.4	39.8-45.5	42.8	1.3-1.5	1.4

The above data indicate that there was considerable bulking of the soil on the burned area, and it would be expected that infiltration capacities would be higher. However, there were fans of eroded soil and ashes below the draws in the burned area and none in the unburned area (15 inches of rain had occurred between January 3 and January 28, 1943).

VEIHMEYER and JOHNSTON [1944; VEIHMEYER, 1951] had been urging us to establish runoff-erosion plots, and the plots mentioned were constructed with their assistance, and using the same designs they have used and reported on in the northern part of the State. Following the natural burn, new plots were started along its edge, one in and one out. Unfortunately, the plots could not be put into operation until April 18, 1943, and by that time 25 inches of rain had occurred since

Table 2--Runoff as a percentage of rainfall and annual erosion in inches depth at the Santa Rosa Ranch in the southwest portion of Riverside County, California
(Plots A1, B1, E, and F each 50 × 50 ft; Plot C = 0.292 ac; Plot D = 0.685 ac; chamise cover on A1, B1, C, and D, chaparral cover on E and F; natural burn on Plot B1, Jan. 3, 1943, and on Plots A1, B1, C, and D, Sep. 30, 1945)

Period	Rainfall Plot B1[a]	A1		B1		C		D		E		F	
		Runoff	Erosion	Runoff	Erosion	Runoff	Erosion	Runoff	Erosion	Runoff	Erosion	Runoff	Erosion
	in	pct	in	pct	in	pct	in	pct	in	pct	in	pct	in
Jan. 14 - July 1, 1942	6.63	...	....	...	....	0	....	0	....	2.8	0	1.4	0
July 1, 1942 - Mar. 18, 1943	27.36[b]	...	....	...[c]	....	0.9	....	...	....	3.0	....	1.5	....
Mar. 18 - July 1, 1943	2.12	0.9	....	5.4	....	0	....	0	....	0.7	....	0.2	....
July 1, 1942 - July 1, 1943	29.24	...	0[d]	.....	0[d]	0.9	0	...	0	2.8	0	1.4	0
July 1 - Dec. 28, 1943	8.54	0.8	....	5.6	....	0	....	0.1	....	1.5	....	1.0	....
Dec. 28, 1943 - July 1, 1944	10.77	2.5	....	4.7	....	0	....	0	....	0.4	....	0.4	....
July 1, 1943 - July 1, 1944	19.31	1.8	0.001	5.1	0.001	0	0	0	0	0.6	0	0.8	0
July 1 - Nov. 15, 1944	8.72	3.9	....	6.2	....	0.1	....	0	....	1.2	....	0.5	....
Nov. 15, 1944 - Feb. 10, 1945	4.50	1.6	....	0.6	....	0	....	0	....	0.7	....	0.2	....
Feb. 10 - Mar. 10, 1945	3.04	0.6	....	0.1	....	0	....	0	....	2.1	....	0.7	....
Mar. 10 - July 1, 1945	3.29	0.2	....	0.1	....	0	....	0	....	2.0	....	0.1	....
July 1, 1944 - July 1, 1945	19.55	2.3	0	2.9	0	0	0	0	0	1.4	0	0.4	0
July 1 - Sep. 28, 1945	1.20	1.1[c]	....	0.1[c]	....	0[c]	....	0[c]	....	0.7	....	0	....
Sep. 28 - Dec. 28, 1945	6.13	5.8	....	14.8	....	...	....	...	....	0.7	....	0.7	....
Dec. 28, 1945 - Mar. 26, 1946	2.98	4.4	....	2.4	....	0.8	....	...	....	0.4	....	0.2	....
Mar. 26 - July 1, 1946	4.38	4.1	....	0.5	....	0	....	...	....	0.2	....	0.2	....
July 1, 1945 - July 1, 1946	14.69	4.6	0.004	6.8	0.001	...	0.14	...	0.10	0.5	0	0.4	0
July 1 - Nov. 21, 1946	7.31	7.8	....	6.0	....	2.5	....	...	....	0.6	....	0.6	....
Nov. 21 - Dec. 31, 1946	4.33	10.1	....	1.8	....	5.2	....	...	....	0.3	....	0.1	....
Dec. 31, 1946 - July 1, 1947	3.00	5.0	....	2.1	....	0.5	....	...	....	0.5	....	0.4	....
July 1, 1946 - July 1, 1947	14.64	7.9	0.097	4.0	0	3.0	0.055	...	....	0.5	0	0.4	0
July 1 - Dec. 13, 1947	1.79	7.8	....	4.9	....	0.7	....	0.4	....	0.7	....	0.7	....
Dec. 13, 1947 - Feb. 11, 1948	3.30	13.0	....	9.0	....	3.6	....	3.4	....	0.4	....	0.3	....
Feb. 11 - Mar. 19, 1948	1.60	4.6	....	3.4	....	1.6	....	1.1	....	0.2	....	0.1	....
Mar. 19 - July, 1948	2.60	3.4	....	2.6	....	1.8	....	...	....	0	....	0.1	....
July 1, 1947 - July 1, 1948	9.29	7.8	0	5.5	0	1.9	0.015	...	0.008	0.5	0	0.5	0
July 1, 1948 - July 1, 1949	13.03	0.9	0	0.3	0	0	0	0	0	0.1	0	0.2	0
July 1, 1949 - July 1, 1950	10.56	1.7	0	1.1	0	0	0	0	0	0.6	0	...	....
July 1, 1950 - July 1, 1951	7.85	2.4	0	2.5	0	0	0	0	0	0.7	0	...	....
July 1, 1951 - July 1, 1952	29.08	6.5	0.001	1.7	0	0.1	0	0	0	0.2	0	..	....

[a] A central location. Rainfall patterns are very similar at all plots, and there are no highly significant differences in total rainfall from plot to plot except that rainfall at E and F averages 4 1/2 pct higher than at the others.

[b] About 25 inches of this rainfall occurred after the fire of January 3, 1943, and before Plots A1 and B1 were completed.

[c] Underscore indicates approximate time of burning on the plot.

[d] From March 18, 1943. Soil had eroded, at least from B1, between January 3, 1943 and March 18, 1943.

the fire. Data in Table 2 appear to indicate that runoff from the burned area exceeded runoff from the unburned area for a period of about two years. In the spring following the burn there was a heavy stand of annuals and grasses on the burned area. By the end of two years, sprouts from the crowns of the deeply rooted chamise had become dense enough to be an appreciable factor in transpiration. (Previous soil-moisture sampling had indicated that the chamise had used all available moisture in the top three feet by late spring or early summer. Rocks prevented sampling to greater depth.)

In September, 1945, another intensely hot natural fire occurred in the area during a period of north wind and low humidity. Large crews fought this blaze, and it was brought under control some days later when the weather changed. The dry litter, in particular, appeared to burn with intense heat. The fire burned over plots A1, B1, C, and D, destroying or damaging the equipment. Plots A1 and B1 were repaired immediately so that continuous records were obtained. Plots C and D were small watersheds in contrast with the 50 × 50 foot plots and required new tanks and tipping buckets. Inability to get materials caused considerable delay, although patching attempts met with enough success on C that only the runoff record up to December 28 was lost.

Data in Table 2, although fragmentary, do indicate that both runoff and erosion were increased for a time following natural burns. This does not seem to result from any reduction in infiltration capacity. The following, from observation, is a possible explanation of the phenomena:

(1) The litter on the soil surface appears to hold considerable quantity of rainfall and to detain that water in overland flow. Thus, a period for infiltration opportunity exists that extends beyond the period of rainfall. Further, the entangled dead leaves and branches inhibit the movement of soil with overland flow of water.

(2) After an intensely hot natural fire in Southern California brushland (usually in the fall or early winter) the litter is completely burned. Usually a part of this burned litter is mixed in with the top inch or two of soil, and the surface soil is in a loose, fine, crumbly condition. Whenever rainfall intensity exceeds infiltration capacity there is little opposition to overland flow, and the soil aggregates are readily transported. The ashes tend to float on the water.

Increased runoff following an intense fire, then, appears to result from a lessened friction factor to overland flow whenever rainfall intensity exceeds infiltration capacity, and increased erosion appears to result from the loose condition of the surface soil. So far as I have observed the plots of VEIHMEYER and JOHNSTON [1944; VEIHMEYER, 1951] in northern California, neither the condition of litter accumulation under brush nor that of a loose condition of the soil surface following burning appear to exist. Differences in the climate of the two regions may therefore account for any differences in results.

A few other observations made on or around the Santa Rosa Ranch plots might be of interest.

(1) The Santa Rosa Ranch is primarily utilized for winter, spring, and early summer grazing. Before the burns, cattle entirely avoided the brush areas around the various plots. For two years or so following the burns, browsing on annuals, grasses, and chamise was very heavy, and has progressively lessened since.

(2) The primary soil of all plots overlies acid igneous bedrock at plots A1, B1, C, and D, and shale at E and F. Chamise covers most all areas of primary soil over acid igneous bedrock, except that sagebrush exists on some of the shallower phases. Following fire in the chamise and sage areas no evidence of any succession of vegetation has been observed, excepting for the few years while the brush is becoming reestablished.

(3) Differential treatments on these plots require a simulation of a natural burn (the College administration early suggested that actual burning during dry weather would be a hazard they could not assume). No way has been found to destroy the litter during safe weather, even by soaking it with gasoline and setting fire to it, or by going over it with a weed burner. Present technique, for which results are not yet reported, involves simply the pruning off of brush near the ground surface, raking off most of the litter, and, so far as possible, leaving the surface soil in a loose crumbly condition.

In conclusion, then, my fragmentary evidence indicates that burning of brushland does not impair, and may improve infiltration capacity, as found by Burgy and Scott. This does not appear, however, to be evidence that erosion and runoff are not increased by burning in Southern California where it is normal for a thick litter to build up under the brush.

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Robert H. Burgy (Division of Irrigation, University of California, Davis, California, Author's closure)--The authors wish to acknowledge the comments of Pillsbury. His conclusions based on field data and observations tend to support the findings of the authors. Further laboratory and field studies underway at present support his contention that changes in soil structure may contribute to increases in infiltration rates after burning.

DISCUSSION OF
"OROGENESIS AS THE FUNDAMENTAL GEOLOGICAL PROCESS"

by J. TUZO WILSON

[Trans., v. 33, pp. 444-449, 1952]

Grover E. Murray (Department of Geology, Louisiana State University, Baton Rouge, Louisiana)--In this article Wilson states on pp. 446-447: ". . . A better average measure is therefore provided by figures recently published by MURRAY [1950], giving the volume of sediments deposited on the Gulf Coast in Mesozoic and Cenozoic times. Murray's data from results of drilling and reasonable extrapolation is that the emerged and offshore portions of shelf underlying the Gulf Coastal Plain contain at least 500,000 cu mi of Cretaceous and later sediments. This was accumulated during 130 million years from a drainage area of 1 1/2 million square miles. It follows that the rate of erosion would have been about one foot per 85,000 years, but this takes no account of the sediments swept out to the deep ocean and the floor of the Gulf of Mexico . . ."

I feel that I must call attention to the fact that the abstract cited (Mesozoic and Cenozoic sedimentary volumes in central Gulf Coast) deals only with that portion of the Gulf Coastal Plain between Texas and Georgia. Although no northern limit to the Central Gulf Coastal Plain is stated in the abstract, the volumes presented are only for the area south of the latitude of Memphis, Tennessee. Further, Upper Jurassic and pre-Upper Jurassic (?) sediments, as well as Cretaceous and later sediments, are included in the volumes cited. The implication by Wilson that 500,000 cu mi represent the total volume of sediments deposited in the Gulf Coastal Plain in Mesozoic and Cenozoic times is therefore misleading. The December 1952 issue of the Bulletin of the Geological Society of America presented six papers analyzing the known volumes of Mesozoic and Cenozoic sediments in the Gulf Coastal Plain of the United States and Mexico. These papers reveal that the minimum known cubic mileage for the emerged (onshore) portion of the Gulf Plain from Georgia to Yucatan, inclusive, are shown in Table 1.

Table 1--Volumes of sediments deposited in the Gulf Coastal Plain during various geologic ages

Region	Cenozoic	Cretaceous	Jurassic and pre-Jurassic (?)	Totals
	cu mi	cu mi	cu mi	cu mi
Mexico, including Yucatan (E. J. Guzman)	161,500 +	110,600 +	31,800 +	303,900 +
Western Gulf Coast (Texas) (Jack Colle, and Others)	211,000 +	131,000 +	111,000 +	453,000 +
Central Gulf Coast (Louisiana, South Ark., Miss., and Alabama) (G. E. Murray)	105,400 +	99,350 +	60,525 +	265,275 +
Eastern Gulf Coast (Florida, Georgia) (Paul and Esther Applin; Lyman Toulmin)	49,500-50,500 +	50,000-60,000 +	10,000-15,000 +	109,500 - 125,500 +
Average Totals	527,900 +	395,950 +	215,825 +	....

These volumes total approximately 1,150,000 cu mi. The total volume for this emerged area may ultimately be proven to be almost twice as great.

Controlled extrapolation indicates that the volumes in the submerged (offshore or shelf) portion of the Gulf Coastal Plain will equal and probably exceed the volumes beneath the emerged portion. The total volume for the submerged portion is estimated to approximate at least 1 1/4 million cubic miles and possibly twice that amount. Accordingly, the minimum total cubic mileage for the combined submerged and emerged areas in the Gulf Coastal Plain from Yucatan to Georgia, inclusive, approximate 2.5 million plus.

If we consider that only the cubic mileage in Texas-Louisiana- south Arkansas-Mississippi-Alabama-west Florida can be attributed to the 1.5 million square mile drainage area cited by Wilson, the known volumes for this emerged area are 718,525 cu mi, and the estimated volumes for the submerged part of this area are 725,000 cu mi, or a total estimated and known volume between Georgia and the Rio Grande of about 1.4 million cubic miles. This is approximately three times the figure cited by Wilson; it certainly represents a minimum. His rate of erosion accordingly should be increased at least two-thirds and probably more.

J. Tuzo Wilson (Department of Physics, University of Toronto, Toronto, Ont., Canada; Author's closure)--The new information given by Murray is welcome and I am grateful to him for presenting the additional information relating tc these estimates which he published in abstract form in 1950. Fortunately it was clear from the text that these estimates were not precise, although some of them were given to six significant figures and I only used them to derive a minimum limit to the order of magnitude of the average rate of erosion.

If Murray's new figures are used, this minimum probable rate of erosion for Cretaceous and Tertiary time in the central United States should be one foot in 30,000 years. This is still some way from the maximum probable limit of one foot in 9,000 years which was derived in another way, and the modification based on Murray's new figures does not in any way alter my final conclusion "that the rate of erosion is such that it has removed a foot in each few tens of thousands of years off continents similar in state to North America."

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

BOMFORD, G., Geodesy, Clarendon Press, 452 pp., 1952, $10.00.

When a book is written for the purpose of coordinating a field of knowledge, its success will depend, not only on the author's skill in organization and judgment in selection, but also upon the extent to which his work is used. Bomford has fulfilled his end of the job admirably; it remains for the geodesist to fulfill his.

In general, each chapter and subsection has been written in such a way that it is possible, by scanning, to get a good general idea of the basic purposes, the minimum requirements, the important difficulties, and the different current practices. Upon more detailed reading one finds rather condensed but still understandable developments of the separate topics.

Thus, this book can be an important aid in the formulation of plans initiating a new national survey organization, and at the same time it can be used as a reference for the principal results and techniques in a specific area.

There are separate chapters on triangulation, on geodetic astronomy, and on gravity and geophysical surveys. The chapter on the Earth's figure and crustal structure is particularly noteworthy, since sources in English for this material are quite scattered. There are seven appendices which go into details on such topics as the geometry of the spheroid, the theory of errors, gravity reduction tables, and spherical harmonics.

The bibliography of some 300 books, articles, and theses is of great value in itself, and the manner in which it has been worked into the text makes it even more valuable.

Aside from the always possible criticism of "Why include this and not that," there is perhaps some ground for criticizing the prose style in which the book is written. We have grown accustomed to the stylistically enjoyable writing of such British scientists as Eddington, Russell, and Jeans, and so it is somewhat of a shock to encounter the clipped prose of the almost outline form in which this book is written. Perhaps this brevity is responsible for the dogmatic sound of the statement on page 2 that "The satisfactory simultaneous adjustment of a very large net is in fact practically impossible."

The U. S. Coast and Geodetic Survey has found that, with IBM equipment, and using the method of variation of geographic coordinates, it is feasible to adjust a triangulation net containing several hundreds of stations.

The reader familiar with the terminology in use in the United States may stumble over such expressions as the "method of rounds," which is our direction method, or "satellite" station for our eccentric station; but fortunately there need be no fear of a fundamental misunderstanding on the score of language.

ALFRED D. SOLLINS

BARTH, TOM. F. W., Volcanic Geology, Hot Springs and Geysers of Iceland, Carnegie Institution of Washington, Pub. 587, xi + 174 pp., 31 pl., 68 fig., Washington, D. C., 1950; paper bound, $5.00; cloth bound, $5.50.

This volume constitutes one of the major contributions in recent years to the study of hot springs and geysers. Iceland contains several thousand known hot springs, of which 30 are active geysers; accordingly, it is an ideal place to make this study.

Barth describes the geological background necessary for this study in Part I. He considers Iceland to belong to the oceanic rock province. In early Tertiary time, enormous masses of lava were erupted; there was extensive volcanism in the Paleocene and Eocene; and volcanism again took place in the Pleistocene and Recent. The recent hot springs and geyser activity bears no direct relation to the Tertiary volcanism.

Part II of this monograph deals with the hot springs and takes up in turn the ground-water hydrology, temperature of hot springs and fumaroles, discharge of the hot springs, and chemical composition of the gases, waters, incrustations, and spring deposits. Many new data are given. The hydrogen-ion concentration in the hot-spring water and its relation to volcanic activity are treated in detail. Barth presents a critical evaluation of the data and interprets them rather fully. Particular attention is given to the chemical and petrographic study of the wall-rock alteration by surface acid waters, neutral waters, and by solutions at greater depths.

Part III considers the phenomena of geysers. Observations made on some of the principal geysers of Iceland are given. Barth then reviews the various theories of geyser action and considers that the theory of Krug von Nidda, published in 1826, is essentially the correct one. The theory of Bunsen applies only to the Great Geyser of Iceland. Thorkelsson's theory of geyser action, which states that "spring gas liberated at elevated temperatures is the agent responsible for geyser action," offers a new mechanism of special significance.

The major factor in producing the hot springs is volcanic heat. Secondary factors are heavy precipitation and a very porous rock formation which rapidly absorbs rain water. The various types of hot springs owe their origin to accidental factors such as topographic conditions, reservoir rocks, and distance from active volcanic centers.

Professor Barth's observations lead to two conclusions at variance with the theory of Bunsen:
(1) "There is no regular increase in the temperature from one eruption to another; most geysers . . . . show a characteristic temperature-depth curve which does not change with time"; and
(2) ". . . . . although the temperature increases with depth, the increase is slower than that of the boiling point with depth."

The major portion of this monograph is Part IV, which contains a description of the hot-spring areas. Data on temperature and pH of the waters are given for a large number of springs. Many of the springs are well illustrated with photographs.

This volume is full of data, interpretations, and ideas. It will be one of the most important source books for volcanologists and petrologists. The critical student will re-read this book for several reasons and each time he will glean much from its contents.

GEORGE T. FAUST

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NOTES AND PERSONALIA

NOTES

Corrigenda--In the issue of October 1952, pages 707 to 712, there is a paper entitled "The circulation of Lake Mendota" by R. A. Bryson and V. E. Suomi. The closing line indicated that it was originally received on February 6, 1950, but this is in error. An earlier paper entitled "Short time variations in temperature in Lake Mendota" by James L. Verber, R. A. Bryson, and V. E. Suomi was received on February 6, 1950, but this was subsequently returned for modification. The paper received on January 10, 1952, while embodying some of the material of the earlier paper, was not, in essence, a revision of that paper.

In the issue of February, 1953, in the paper by Carl I. Aslakson, on page 9, Figure 7, at top and bottom are indicated 70° as the longitude. These should read 79°.

Midwest Inter-Library Center--The Midwest Inter-Library Center, established with the aid of a substantial grant in 1949, supported and controlled by 16 member universities, has opened its new three-million-volume capacity library building in Chicago. On February 28, 1953, a meeting of geologists was held to consider the cooperative acquisition of less-used but important library materials to supplement the collections of the individual libraries, thus extending substantially the facilities that are limited even in the most extensive libraries.

Experiment in the use of helicopters in triangulation--The Engineer Research and Development Laboratories of the Corps of Engineers have recently completed tests to use helicopters in triangulation work, especially in inaccessible terrain. The tests were made on an area about 30 × 60 mi in Arizona by simultaneous observations on a light suspended below a helicopter. The data are now being analyzed, checking determined latitudes, longitudes, and elevations against results secured by conventional survey methods.

Work in the Pacific by H.M.S. Challenger--The *Challenger* was engaged on work in the Pacific from October, 1950, to May, 1952, covering a course: Panama Canal, San Diego, Esquimalt, Queen Charlotte Islands, Honolulu, Adak, Kure, Manus, Auckland, Fiji, Funafuti, Nukufetau, Manus, Kure, Yokosuka, Hong Kong, Singapore. Work included studies of magnetic variation and atoll and other structure using seismic refraction technique and the more usual oceanographic observations.

Endeavor prizes--Five prizes will be awarded by *Endeavor* and the British Association for the Advancement of Science for essays on any of eight subjects, including Radio-Astronomy, Power and Civilization, and Scientific Societies and Their Role. Essays must not exceed 4000 words, must be typewritten, and received by June 1, 1953, by the Assistant Secretary, British Association for the Advancement of Science, Burlington House, Piccadilly, London, W.1, England. Further details may be secured by writing to the same address. Two of the prizes are for writers under 18.

Third International Conference on Soil Mechanics and Foundation Engineering to be held in Switzerland--This Conference will be held in Zurich, Switzerland, August 16-27, 1953. Interested persons should address inquiries to A. von Moos, General Secretary, Gloriastr. 39, Zurich 6, Switzerland, or to the Chairman of the U. S. National Council, A. E. Cummings, Room 1308, 140 Cedar St., New York 6, N. Y.

New Italian publication in geophysics--A new publication, *Geofisica e Meteorologia*, is being published by the Italian Society of Geophysics and Meteorology. Volume 1, number 1, dated January-February, 1953, contains five papers, and reports, reviews and notes. Mario Bossolasco, via

Balbi 5, Genova, Italy, is the Secretary of the Society. The subscription rate is $5.00 per year.

New publication of the National Speleological Society--A new publication entitled *Occasional Papers*, serving as a medium for technical and scientific papers in speleology has been announced. The *Bulletin* of the Society has been renamed *The American Caver* and will continue to be the Society's medium for non-technical and popular papers.

Summer course in marine biology at Florida State University--A basic or introductory course in marine biology will be offered at the Alligator Harbor Laboratory of the Oceanographic Institute of Florida State University June 15-July 22, 1953. Interested persons should write to the Registrar of the University at Tallahassee.

Expedition of the American Geographical Society--An expedition to the borders of Venezuela and Colombia, searching for the headwaters of the Macoita and Aponcito Rivers is now under way. William Phelps, Jr. is its leader.

Fellowship program of the Humble Oil and Refining Company--In addition to the continuation of previously established fellowships at the University of Texas, University of Oklahoma, and Louisiana State University, a new one has been established at the University of California at Los Angeles. The designation of recipients is entirely in the hands of the Universities.

New scholarship in mining engineering at Lehigh University--The John T. Fuller Endowment Fund "to grant a scholarship in the Department of Mining Engineering to a deserving Pennsylvania boy" has been established, the award to be made on the basis of financial need, character, and high scholastic achievement.

PERSONALIA

John Emery Adams of the Standard Oil Company of Texas has been elected President of the American Association of Petroleum Geologists.

Leason H. Adams has retired as Director of the Geophysical Laboratory of the Carnegie Institution of Washington.

Roger Adams, Professor of Chemistry at the University of Illinois, has been named to receive the A. W. von Hofmann Memorial Medal of the Gesellschaft Deutscher Chemiker.

Alceu Fabio Barbosa has been elected President of the Geological Society of Brazil.

Ralph E. Digman of Harpur College, Endicott, N. Y., has been elected Secretary of the Association of Geology Teachers.

Armand J. Eardley of the University of Utah has been named Editor of the *Bulletin* of the American Association of Petroleum Geologists.

Herbert N. Eaton, Chief of the Hydraulics Section of the National Bureau of Standards in charge of the Hydraulic Laboratory has recently retired. K. Hilding Beij, Assistant Chief of the Section, is now serving as acting Chief.

Walter L. Elsasser, Professor of Physics at the University of Utah, will be Visiting Professor of Geophysics at the University of Alaska during the summer and will work at the Geophysical Institute during August. He will give a series of lectures on Radiative Heat Transfer in the Upper Atmosphere.

Gerald M. Friedman of the University of Cincinnati has been elected Treasurer of the Association of Geology Teachers.

M. M. Leighton, Chief of the Illinois Geological Survey, has recently given the annual series of Bownocker Lectures at Ohio State University.

Joe Webb Peoples of Wesleyan College, Middletown, Conn., has been elected Vice President of the Association of Geology Teachers.

Alfred O. Quinn, Chief of Engineering and Field Surveys of the Aero Service Corporation, has been elected President of the American Society of Photogrammetry.

Howard S. Rappleye, Chief of the Section of Leveling of the U. S. Coast and Geodetic Survey, has retired after more than 36 years of service in the Survey.

Vincent J. Schaefer of General Electric Research Laboratory has been given the Robert M. Losey Award of 1952 by the Institute of the Aeronautical Sciences for his research work in cloud physics.

Robert B. Sosman, Professor of Ceramics at Rutgers University, has been given the Albert Victor Bleininger Award for distinguished achievement in the field of ceramics. The award is made annually by the Pittsburgh Section of the American Ceramic Society.

Orville F. Tuttle of the Geophysical Laboratory, Carnegie Institution of Washington, has been named Professor of Geochemistry and Head of the Department of Earth Sciences, Pennsylvania State College.

Theodore von Karman recently presented a series of lectures on Aerothermodynamics and Combustion Theory at the Guggenheim Jet Propulsion Center at Princeton University.

Jake Moon, Party Chief with Geophysical Service, Inc., was killed by an explosion near Poza Rica, Vera Cruz, Mexico, on July 22, 1952, at the age of 36. He was born in Garfield, Arkansas, and studied at Kansas State College, and had devoted his entire career, from 1935 until his death with Geophysical Service in various capacities on geophysical exploration work. He had been a member of AGU since 1945.

Henrik Renquist of Helsinki, Finland, died February 23, 1953, at the age of 70. He received his doctorate in 1917 after having begun his professional career as a geologist in 1907. From 1919 to 1931, he worked with the Finnish Oceanographic Institute, and from 1931 to 1946, when he retired, he was Director of the Finnish Hydrographic Bureau, also undertaking teaching work at the University of Helsinki and the supervision of the seismograph station at Helsinki during this same period. He was a member of the Finnish Academy of Sciences and a member of the Finnish National Committee of IUGG. In the IUGG, especially in the Association of Hydrology, he was very active and was Chairman of the Association's Commission on Limnology for many years.

Frank H. Tyro, Assistant Project Engineer for the Flathead Irrigation Project, U. S. Indian Irrigation Service in Montana, died October 20, 1952, at the age of 38. He was born in Salt Lake City in 1915, attended Montana State Normal College and Montana State University. He began his career on various hydraulic investigations such as ground water studies, canal and reservoir problems, and runoff forecasts relating to irrigation needs for the Flathead project, the Bureau of Reclamation, and later for the Corps of Engineers, U. S. Army. Since 1944, his services had been continuously with the Flathead Project. He had been a member of AGU since 1948.

SPECIAL ANNOUNCEMENTS

Regional Meeting in Minneapolis, Minnesota, August 31, 1953--As noted in previous Special Announcements [see Feb. 1953, p. 157, and Dec. 1952, p. 945] the Thirtieth Regional Meeting will be held in Minneapolis, August 31, 1953. Plans for the program are well along. Interested persons should get into touch with the Chairman of the Committee (Martin E. Nelson, U. S. Engineer Office, Post Office Bldg., St. Paul, Minn.) or the Secretary (Roy F. Warner, 1872 N. Howard St., St. Paul,9, Minn.) or some other member of the Committee (Paul C. Benedict, M. C. Boyer, and Lorenz G. Straub).

Need for back Transactions--Anyone who does not maintain a permanent file of the Transactions is urged to return copies with which he is through to AGU. Senders will be reimbursed postage expenses. Especially sought are February, April, and June of 1947, February and June of 1949, February 1950, February, April, and August of 1951, and all of 1952.

Back Transactions of AGU available on microcards--The Society of Exploration Geophysicists has made arrangements with the Microcard Foundation to reproduce important geophysical literature on microcards. Included in the project is the microcarding of the Transactions from volumes 1-32 (1920 to 1951 inclusive). The Transactions will be available by volume only, and particular papers, numbers, or parts cannot be supplied. The project is on a trial basis, to run to December 31, 1954. Interested persons should write to the Society of Exploration Geophysicists, P. O. Box 7248, Tulsa 18, Oklahoma.

ADDITIONS TO THE MEMBERSHIP, SEPTEMBER 11, 1952 TO MARCH 10, 1953

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Urey, Dr. Harold C., Institute for Nuclear Studies, University of Chicago, Chicago, Ill. (afh)
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Wahl, Dr. Eberhard W., 15 Fairfield St., Watertown 72, Mass. (c)
Walsh, Mr. William P., 47 Mary St., Arlington 74, Mass. (bh)
Walton, Mr. C. Leroy, 2917 Harvard Ave., Fresno, Calif. (g)
Walton, Mr. J. I., Exploration Dept., N. V. Standard-Vacuum Pet. Mij., Sungei Gerong, Palembang, Sumatra, Indonesia (b)
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Transferred to Active Status

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AMERICAN
GEOPHYSICAL
UNION

UNSELFISH
COOPERATION
IN RESEARCH

PROGRAM

THIRTY - FOURTH ANNUAL MEETING

In the Building of the National Research Council - National Academy of Sciences,
and the Auditorium of the General Services Building,
Washington, D. C.

May 4-6, 1953

SCHEDULE OF SESSIONS

Day	Date	Time	Room 1[a]	Room 2[a]	Room 3[a]
	1953				
Monday	May 4	09h 00m	Hydrology	Geodesy	Meteorology
		14h 00m	Meteorology[b]	Volcanology	Hydrology
		20h 00m	....	Evening Session	....
Tuesday	May 5	09h 00m	Symposium	Oceanography	Hydrology
		14h 00m	Hydrology	Tectonophysics	T. M. and E.
		20h 00m[c]	....	....	....
Wednesday	May 6	09h 00m	T. M. and E.	Seismology	Oceanography
		14h 00m	General Assembly	....	....

[a] For key to room numbers, see page 328.

[b] Session held jointly by Section of Meteorology and the American Meteorological Society.

[c] The Smoker will be held in the Auditorium of the Cosmos Club, Florida Avenue at Massachusetts Avenue, Northwest, from 20h to 22h.

OFFICERS OF THE UNION

John A. Fleming, Honorary President
Walter H. Bucher, President
F. W. Reichelderfer, Vice President
K. Hilding Beij, General Secretary
Waldo E. Smith, Executive Secretary

COMMITTEE ON MEETINGS

J. P. Marble, Chairman
Woodrow C. Jacobs
Herbert S. Riesbol
Walter E. A. Ruska
Glenn E. Stout
Frank J. Veihmeyer

(Note: This program is paginated in the Transactions of 1953. Preserve for binding.)

OFFICERS OF THE SECTIONS

Section	President	Vice President	Secretary
Geodesy	Harry H. Hess	A. J. Hoskinson	Frank L. Culley
Seismology	Perry Byerly	L. M. Murphy	James T. Wilson
Meteorology	Benjamin Holzman	Hurd C. Willett	Woodrow C. Jacobs
Terrestrial Magnetism and Electricity	J. W. Joyce	Victor Vacquier	L. R. Alldredge
Oceanography	A. C. Redfield	Roger R. Revelle	R. H. Fleming
Volcanology	Esper S. Larsen, Jr.	Thomas P. Thayer	Felix Chayes
Hydrology	F. J. Veihmeyer	Walter B. Langbein	Ray K. Linsley
Tectonophysics	Robert Balk	Francis Birch	Wilbur S. Burbank

GENERAL MEETINGS OF THE UNION

EVENING SESSION

Monday, May 4, 1953, 20h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Symposium on the Earth's Interior - First Session
(1) S. K. RUNCORN: The Earth's Core
Fifteenth Award of the William Bowie Medal
(a) Citation by Perry Byerly
(b) Presentation by Walter H. Bucher, President
(c) Response
Social hour and refreshments

MORNING SESSION

Tuesday, May 5, 1953, 09h 00m, Room 1 (Auditorium, National Academy of Sciences)

Symposium on the Earth's Interior - Second Session
Discussion of the paper of S. K. Runcorn on The Earth's Core presented at the Evening Session
Discussants: E. H. VESTINE and WALTER M. ELSASSER
Open discussion
(2) FRANCIS BIRCH: Elasticity and Constitution of the Earth's Mantle
(3) J. VERHOOGEN: Petrological Evidence on the Temperature Distribution in the Mantle of the Earth
Discussants of papers (2) and (3): HARVEY BROOKS and DAVID T. GRIGGS
Open discussion

SMOKER

Tuesday, May 5, 1953, 20h 00m to 22h 00m, Auditorium of the Cosmos Club,
Florida Avenue at Massachusetts Avenue, Northwest

This is our usual informal gathering where opportunity is afforded to renew old acquaintances and make new ones. No program is planned. Refreshments will be served. Tickets are 75 cents each, and will be sold in advance at the Main Registration Desk in the Building of the National Academy of Sciences - National Research Council, and by the Section Secretaries or others whom they may designate. Ladies are invited.

GENERAL ASSEMBLY

Wednesday, May 6, 1953, 14h 00m, Room 1 (Auditorium, National Academy of Sciences)

Lecture
ROGER REVELLE: Preliminary Report on the Capricorn Expedition to the South Pacific

Business Meeting (Effort will be made to keep this within our usual half hour. Please plan to attend.)

(1) Reports of officers and special and standing committees, including:
  (a) General Secretary's report
  (b) Report of the Committee on Resolutions (Mary C. Rabbitt, Chairman; Werner A. Baum; and Francis G. Wells)
(2) Unfinished business
(3) New business

MEETINGS OF THE SECTIONS

SECTION OF GEODESY

Monday, May 4, 1953, 09h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session
  Reports of committees, announcement of results of Section elections, and other business
Scientific Session
  (1) ARTHUR S. G. GRANT: Notes on the atmospheric refractive index in Canada from aircraft meteorological soundings
  (2) JOHN C. DUECKER: Gravity traverse in northeastern Pennsylvania
  (3) STEPHAN THYSSEN-BORNEMISZA: Development of a new technique for measuring the vertical gradient of gravity
  (4) PETER HIDNERT and RICHARD K. KIRBY: A new method for determining coefficients of linear thermal expansion of invar geodetic surveying tapes
  (5) JOHN ALOYSIUS O'KEEFE: The isoparametric method of mapping one ellipsoid on another
  (6) C. H. NEY: Geographical positions from stellar asimuths
  (7) T. J. KUKKAMÄKI: Results obtained by the Finnish solar eclipse expeditions, 1947
  (8) HUGH C. MITCHELL: The economy of the controlled survey
  (9) MANUEL MEDINA: Geodetic work in Mexico from June 1952 to May 1953

SECTION OF SEISMOLOGY

Wednesday, May 6, 1953, 09h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session
  Reports of committees, announcement of results of Section elections, and other business
Scientific Session
  (1) PAUL LIEBER: On wave propagation in visco-elastic materials
  (2) CHARLES B. OFFICER, JR: The refraction arrival in water-covered areas
  (3) WILLIAM L. DONN: Direction studies using ~~microseism~~-ground-particle orbits
  (4) FRANK PRESS and MAURICE EWING: Performance of Columbia long-period vertical seismograph
  (5) HENRY F. BIRKENHAUER: Seismic vibrations in machine tools
  (6) JACK OLIVER, FRANK PRESS, and MAURICE EWING: Crustal structure of the arctic regions from the Lg phase
  (7) BENO GUTENBERG, HUGO BENIOFF, and C. F. RICHTER: Progress report on investigations of the Southern California earthquake of July 21, 1952

SECTION OF METEOROLOGY

Monday, May 4, 1953, 09h 00m, Room 3 (Auditorium, General Services Building)

Business Session
  Reports of committees, announcement of results of Section elections, and other business
Scientific Session
  (1) GILBERT N. PLASS: The carbon dioxide theory of climatic change (20 minutes)
  (2) RONALD L. IVES: Early Wisconsin winds in central Utah (15 minutes)
  (3) CHRISTIAN E. JUNGE: A contribution to the question of the chemical composition of atmospheric nuclei (20 minutes)
  (4) C. H. KEITH and A. B. ARONS: The growth of sea-salt particles by condensation of atmospheric water vapor (20 minutes)
  (5) A. H. WOODCOCK and D. C. BLANCHARD: Sea salt in the air, and in the rains of Hawaii (20 minutes)
  (6) C. E. ANDERSON and H. GLAZER: The GRD adiabatic expansion chamber: A new tool for cloud physics research (20 minutes)

Monday, May 4, 1953, 14h 00m, Room 1 (Auditorium, National Academy of Sciences)

Scientific Session jointly with the American Meteorological Society

(7) H. W. DUBACH and W. E. MALONEY: A discussion of the meteorological and oceanographical conditions resulting in the storm disaster in the Irish and North seas on February 1, 1953 (20 minutes)

(8) R. E. BURNS, L. B. BERTHOLF, and C. C. BATES: The destructive storm surge of March 18, 1952 along the Gulf Coast: I, Oceanographic aspects; II, Meteorological aspects (20 minutes)

(9) GERHARD NEUMANN: Some relationships between the atmospheric circulation and sea surface temperatures (20 minutes)

(10) BASIL W. WILSON: Generation of long period seiches in Table Bay Harbor, Cape Town, by barometric oscillations (20 minutes)

(11) E. B. CALLAWAY: Ice-thickness forecasting as applied to Baffin Bay and Davis Strait area (20 minutes)

(12) DALE F. LEIPPER: The forecasting problem in oceanography (15 minutes)

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

Tuesday, May 5, 1953, 14h 00m, Room 3 (Auditorium, General Services Building)

Business Session

Reports of committees, announcement of results of Section elections, and other business

Scientific Sessions

(1) ZDENKO FRANKENBERGER: The compensation method for absolute measurement of the terrestrial magnetic field (15 minutes)

(2) JULES AARONS and MARTHA HENISSART: Low-frequency magnetic noise in the range 1/2 to 20 cycles per second (15 minutes)

(3) ELWOOD MAPLE: The short-period variations of the horizontal component of the geomagnetic field at Point Barrow, Alaska (15 minutes)

(4) L. W. MORLEY: Problems of aeromagnetometry within the auroral zone (15 minutes)

(5) S.K. RUNCORN: The electrical conductivity of the Earth's mantle (20 minutes)

(6) SYDNEY CHAPMAN and MASAHISA SUGIURA: The average storm-time variation of the electric current systems of magnetic storms (15 minutes)

(7) EDWIN J. CHERNOSKY: On a quasi-centennial variation of sunspot number (15 minutes)

(8) H. FREEBORN JOHNSTON: List of magnetic observatories and thesaurus of values (by title)

Wednesday, May 6, 1953, 09h 00m, Room 1 (Auditorium, National Academy of Sciences)

(9) L. M. BRANSCOMB, R. J. SHALEK, and T. W. BONNER: Intensity distributions in nitrogen bands excited in auroras and by high energy protons and hydrogen atoms (20 minutes)

(10) SYDNEY CHAPMAN: Notes on auroral geometry and optics, I, To locate an elevated point viewed from two ground stations in the same diametral plane (10 minutes)

(11) JOSEPH C. CAIN: Auroral radio-echo table and a diagram for a station in geomagnetic latitude 56° (10 minutes)

(12) RITA C. SAGALYN and GERARD A. FAUCHER: Relation between electrical and meteorological parameters in the free atmosphere (15 minutes)

(13) SAMUEL C. CORONITI and ELDON HEATON: The electrical conductivity of the atmosphere over the Pacific Ocean (15 minutes)

(14) SERGE A. KORFF: Effects of the cosmic radiation on terrestrial isotope distribution (10 minutes)

(15) BERNARD J. DUNN: The use of square voltage waves to determine the mobilities of gaseous ions (15 minutes)

(16) SANFORD C. GLADDEN: Procedures employed in the quality control of ionospheric data by the National Bureau of Standards (20 minutes)

(17) C. R. WILSON: Notes on auroral hydrogen and the evolution of an auroral display (10 minutes)

SECTION OF OCEANOGRAPHY

Tuesday, May 5, 1953, 09h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session

Reports of committees, announcement of results of Section elections, and other business

Scientific Sessions

(1) **KENNETH N. GRANTHEM:** Wave run-up on sloping structures
(2) **R. L. WIEGEL, D. A. PATRICK and H. L. KIMBERLEY:** Surf conditions and beach profile-records for Santa Margarita Beach, Oceanside, California, for 1949
(3) **D. A. PATRICK:** Comparison of beach elevation at limits of backwash and uprush with the U. S. Coast and Geodetic Survey tide predictions on several Pacific coast beaches
(4) **CHARLES L. BRETSCHNEIDER and ROBERT O. REID:** Changes in wave height due to bottom friction, percolation, and refraction (15 minutes)
(5) **ALFRED C. REDFIELD:** Interference phenomena in the tides of the Woods Hole region (20 minutes)
(6) **W. E. MALONEY and R. E. BURNS:** A method for the determination of the natural period of enclosed or semi-enclosed basins (12 minutes)
(7) **W. ARMSTRONG PRICE:** Energy classification of coasts and shorelines (20 minutes)
(8) **FRANCIS A. RICHARDS:** Oxygen-density relationships in three detailed cross-sections of the Gulf Stream
(9) **FRANK CHEW:** Results of hydrographic and chemical investigations in the region of the "Red Tide" bloom on the west coast of Florida in November, 1952 (15 minutes)
(10) **LOUIS A. POST:** The role of the Gulf Stream in the prediction of iceberg distribution in the North Atlantic (15 minutes)

Wednesday, May 6, 1953, 09h 00m, Room 3 (Auditorium, General Services Building)

(11) **RICHARD H. FLEMING:** Activities of the Department of Oceanography, University of Washington, 1952 (15 minutes)
(12) **W. C. KRUMBEIN:** Statistical designs for sampling beach sand (15 minutes)
(13) **ALBERT EHRLICH:** Subsurface density inversions off Nantucket Island (15 minutes)
(14) **ALLEN H. SCHOOLEY:** A simple method for measuring the statistical distribution of sea-surface slopes (15 minutes)
(15) **WILBUR MARKS:** Power spectrum analysis of ocean waves by the use of aerial stereophotography (15 minutes)
(16) **GERHARD NEUMANN:** On the energy distribution in ocean-wave spectra at different wind velocities
(17) **WILLARD J. PIERSON, JR.:** An interpretation of the observable properties of "sea" waves in terms of the power spectrum of the Gaussian record (20 minutes)
(18) **R. W. JAMES:** Concerning the power spectrum of ocean waves (10 minutes)
(19) **KOJI HIDAKA:** Theoretical studies on the general circulation of the Pacific (20 minutes)
(20) **KOJI HIDAKA:** A contribution to the theory of upwelling and coastal currents (20 minutes)
(21) **JOSEPH E. O'HARE:** A shock-wave hypothesis on the origin of the oceanic tide (20 minutes)
(22) **JACK OLIVER, A. P. CRARY, and R. COTELL:** Elastic waves in Arctic pack ice

SECTION OF VOLCANOLOGY

Monday, May 4, 1953, 14h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session

Reports of committees, announcement of results of Section elections, and other business

Scientific Session

(1) **R. M. FARQUHAR, R. D. RUSSELL, and J. TUZO WILSON:** The determination of the ages of lead ores by means of their isotopic constitutions (14 minutes) (presentation by Mr. Farquhar)
(2) **R. D. RUSSELL, R. M. FARQUHAR, and G. L. CUMMING:** The isotopic constitution of Sudbury galenas (14 minutes) (presentation by Mr. Russell)
(3) **DAVID GOTTFRIED:** The age and relationships of radioactivity, lead content and physical properties of zircon crystals from Ceylon (14 minutes)
(4) **H. D. HOLLAND, D. A. SCHULZ, and M. N. BASS:** The effect of nuclear radiation on the structure of zircon (14 minutes)
(5) **J. A. JACOBS:** Problems connected with the cooling of the Earth (14 minutes)
(6) **J. H. SWARTZ:** Thermal gradients in Eniwetok Atoll

(7) **L. O. NICOLAYSEN, L. T. ALDRICH, and J. B. DOAK:** Age measurements on African micas by the strontium-rubidium method (14 minutes) (presentation by Mr. Nicolaysen)
(8) **CLAIRE C. PATTERSON, H. S. BROWN, M. G. INGHRAM, E. S. LARSEN, JR., and G. R. TILTON:** The distribution of lead and uranium in a Precambrian granite (14 minutes) (presentation by Mr. Patterson)
(9) **R. D. RUSSELL, H. A. SHILLIBEER, and A. K. MOUSUF:** The branching ratio of potassium-40 (14 minutes) (presentation by Mr. Russell)
(10) **HANS E. SUESS:** A note on the isotopic composition of atmospheric hydrogen (14 minutes)

SECTION OF HYDROLOGY

Monday, May 4, 1953, 09h 00m, Room 1 (Auditorium, National Academy of Sciences)

Business Session
- (a) Report of Officers
- (b) Announcement of results of Section elections
- (c) Report of Committee on Honors and Awards
- (d) Other business

Scientific Sessions

(R1) **L. L. HARROLD:** Report of Research Committee on Infiltration (10 minutes)
(1) **N. L. STOLTENBERG:** Infiltration - some theoretical and practical aspects (15 minutes)
(2) **V. S. ARONOVICI:** The application of the ring infiltrometer to diagnosis of irrigation problems in Southern California (presentation by L. L. Harrold) (15 minutes)
(R2) **J. L. HOUGH:** Report of Research Committee on Lakes (10 minutes)
(R3) **A. R. CROFT:** Report of Research Committee on Evaporation and Transpiration (10 minutes)
(3) **M. J. GILBERT:** A simple field method for measuring maximum evapotranspiration (10 minutes)
(R4) **J. F. POLAND:** Report of Research Committee on Ground Water (10 minutes)
(4) **S. IRMAY:** An electrical analogy method for solving problems of two-dimensional flow in non-homogeneous isotropic media (presented by title)
(5) **N. J. LUSCZYNSKI:** Computation of recharge to the Lloyd Sand member of the raritan formation on Long Island, N. Y. (20 minutes)
(6) **DOAK COX and WALTER MUNK;** The diffusion of tides into the volcanic rock of Hawaii: A method for estimating subsurface permeability (15 minutes) (presentation by Dr. Munk)
(R5) **F. L. RHODES:** Report of Research Committee on Snow (10 minutes)

Monday, May 4, 1953, 14h 00m, Room 3 (Auditorium, General Services Building)

(R6) **J. W. JOHNSON:** Report of Research Committee on Dynamics of Streams (10 minutes)
(7) **SAM SHULITS:** Graphical analysis of trend profile of a shortened section of river (15 minutes)
(8) **J. T. HACK:** The geologic factors on the longitudinal stream profile (15 minutes)
(9) **A. N. STRAHLER:** Revisions of Horton's quantitative factors in erosional terrain (15 minutes)
(R7) **W. O. FIELD:** Report of Research Committee on Glaciers (10 minutes)
(10) **T. L. PEWE and L. W. TAYLOR:** Ablation measurements on Black Rapids Glacier, Alaska (presentation by Mr. Pewe) (10 minutes)
(11) **J. E. FISHER:** Temperature gradients found in a (cold) glacier in the Alps (15 minutes)
(12) **C. J. HEUSSER, R. L. SCHUSTER, and A. K. GILKEY:** Post-Wisconsin glacier maximum in the Juneau Ice Field, Alaska (presentation by Dr. Heusser) (15 minutes)
(R8) **G. B. BODMAN:** Report of Research Committee on Physics of Soil Moisture (10 minutes) (presentation by F. J. Veihmeyer)
(13) **C. H. M. van BAVEL, E. E. HOOD, and N. UNDERWOOD:** Sample size in the neutron scattering method for measuring soil moisture (presentation by Dr. van Bavel) (15 minutes)
(14) **K. G. REINHART and R. E. TAYLOR:** Infiltration and available soil-moisture storage (presentation by Mr. Reinhart) (15 minutes)

Tuesday, May 5, 1953, 09h 00m, Room 3 (Auditorium, General Services Building)

(R9) **C. F. IZZARD:** Report of Research Committee on Runoff (10 minutes)
(15) **H. C. S. THOM:** The generalized log-normal distribution applied to stream discharge (20 minutes)
(16) **W. C. ACKERMANN:** Effect of 15 years of forest-cover improvement upon hydrologic characteristics of White Hollow watershed (15 minutes)

(17) **LOUIS H. BEAN**: Long-range forecasts of floods in the Columbia and Missouri Rivers (15 minutes)

(R10) **W. C. ACKERMANN**: Report of Research Committee on Precipitation (10 minutes)

(18) **J. L. H. PAULHUS**: A frequency study of ten- to 120-minute rainfall intensities (20 minutes)

(19) **R. F. BLACK**: Precipitation at Barrow, Alaska, greater than recorded (10 minutes)

(20) **L. L. WEISS** and **W. T. WILSON**: Evaluation of significance of slope changes in double-mass curves (presentation by Mr. Weiss) (15 minutes)

(21) **J. I. BURNS**: Small scale topographic effects on precipitation distribution in San Dimas Experimental Forest (presentation by W. D. Potter) (15 minutes)

(22) **J. T. RIEDEL**: Topographically adjusted mean annual isohyetal map for New England-New York area (20 minutes)

(23) **L. H. MADOW**: Estimation of mean rainfall with various gage densities in a dense rain-gage network (presentation by G. E. Stout, discussion by E. E. SANDERSON) (25 minutes)

Tuesday, May 5, 1953, 14h 00m, Room 1 (Auditorium, National Academy of Sciences)

(24) **P. E. DAMON** and **P. F. KURODA**: On the natural radioactivity of rainfall (presentation by Mr. Damon) (20 minutes)

(25) **JOHN SHERROD, JR.**: A bibliography on snow, ice, and permafrost (10 minutes)

(26) **S. A. SCHUMM**: Erosion measured on badland slopes (15 minutes)

Symposium on Land Erosion

(27) **H. V. PETERSON**, Chairman of Research Committee on Land Erosion: Introductory remarks (5 minutes)

(28) **L. M. GLYMPH**: Water erosion problems and control on non-irrigated agricultural lands (20 minutes)

(29) **J. E. FLETCHER, KARL HARRIS, H. B. PETERSON**, and **V. N. CHANDLER**: Piping (15 minutes)

(30) **M. R. HUBERTY**: Some observations on soil erosion in the middle and eastern Mediterranean area (20 minutes)

(31) **J. D. SINCLAIR**: Erosion in the San Gabriel Mountains of California (presentation by H. C. Storey) (15 minutes)

(32) **A. W. ZINGG**: Wind Erosion on the Plains area (20 minutes)

(33) **H. W. ANDERSON**: Suspended sediment as related to watershed streamflow, soils, topography, and land use (presentation by H. G. Wilm) (20 minutes)

SECTION OF TECTONOPHYSICS

Tuesday, May 5, 1953, 14h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session

Reports of committees, announcement of results of Section elections, and other business

Scientific Session

(1) **JOEL E. FISHER**: Arguments for a solid central core of the Earth at 0°K (10 minutes)

(2) **DAVID GRIGGS** and **FRANCIS J. TURNER**: Deformation of rocks at moderate temperatures and pressures (15 minutes)

(3) **WILLIAM W. RUBEY**: Tectonic consequences of crustal growth by selective fusion (20 minutes)

(4) **J. TUZO WILSON**: On grabens, rifts, major wrench faults and straight chains of islands (20 minutes)

(5) **MATT WALTON**: Differential metamorphic mobilization and the Adirondack eruptive sequence (20 minutes)

(6) **WILBUR S. BURBANK**: Thermodynamics of metasomatism, energy conversion, and flow of heat in the Earth's crust (20 minutes)

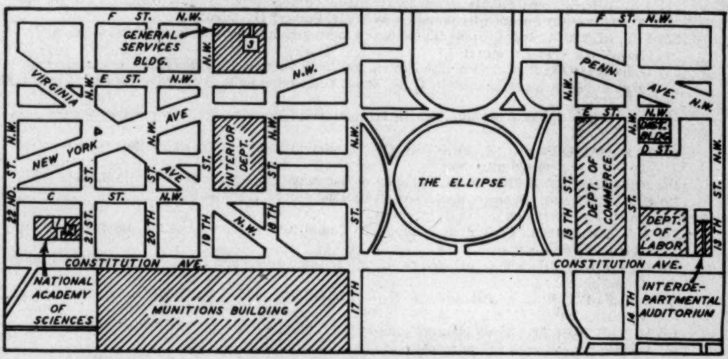
(7) **BRIAN MASON**: Polymorphism and orogeny (10 minutes)

NOTES

Room Reservations--Make hotel or room reservations directly with the hotel of your choice as soon as possible (see December 1952 issue, p. 945, for word concerning hotels at which block bookings have been made). Bear in mind that advance bookings on which deposits have not been made are cancelled two weeks in advance, and thus, during this interval, chances of making a reservation may be quite good. Even though no advance reservation has been made, it is possible to arrange for quarters after arrival in Washington through the Housing Committee of the Washington Board of Trade (204 Evening Star Building, Washington 4, D. C., telephone REpublic 7-2600); but they may find it necessary to direct you to a tourist home.

Registration--All members and guests attending any session are requested to complete cards of registration at the Main Registration Desk at the entrance to the Building of the National Research Council - National Academy of Sciences, where Receptionists will be available to supply information regarding meetings, membership, telephone and mailing facilities, and other local matters. An auxiliary Registration Desk will also be maintained at the entrance to Room 3 (Auditorium, General Services Building). There is no charge for registration.

Map showing locations of meeting rooms


F ST. N.W.
GENERAL SERVICES BLDG.
3
VIRGINIA
E ST. N.W.
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NEW YORK AVE
N.W.
22 ND. ST.
C ST. N.W.
21 ST.
20 TH ST.
19 TH
18 TH ST.
INTERIOR DEPT.
1
2
CONSTITUTION AVE.
NATIONAL ACADEMY OF SCIENCES
MUNITIONS BUILDING
17 TH ST.
THE ELLIPSE
F ST. N.W.
PENN. AVE. N.W.
E ST.
15 TH ST.
DEPT. OF COMMERCE
DIST. BLDG.
D ST.
DEPT. OF LABOR
13 TH ST.
14 TH
CONSTITUTION AVE.
INTERDEPARTMENTAL AUDITORIUM

Key to room numbers

1--Auditorium, National Academy of Sciences - National Research Council Building
2--Lecture Room, National Academy of Sciences - National Research Council Building
3--Auditorium, General Services (Old Interior) Building

Discussion--Within the available time, opportunity will be given for discussion from the floor following the oral presentation of a paper. Discussants are urged to prepare their comments for consideration for publication with the paper.

Resolutions--Chairman Mary C. Rabbitt (phone REpublic 7-1820, Ext. 4176) of the Union's Committee on Resolutions, desires to have this Committee fully advised by 15h 00m, Tuesday, May 5, 1953, of any resolutions to be submitted in order that this Committee may have opportunity to prepare them in final form for presentation at the Business Session of the Union on Wednesday afternoon, May 6, 1953. Each resolution presented to the Committee should include (a) names of original submitters, (b) whether presented to a Section, and action taken, and (c) whether action is desired in the Business Session or whether the resolution is to be regarded as being only for a particular Section or as one to be more effective as a general resolution of the whole Union. In addition to the Union's Committee on Resolutions, each Section has a Resolutions Committee. Section officers can supply information concerning these.

Conference Room--The Reading Room (west end of the first floor behind the Library) of the National Academy of Sciences is available by arrangement for conferences. See J. Putnam Marble, Chairman of the Committee on Meetings, for assignment.

Lounge--The Board Room (behind the Lecture Room), the Library (opposite the Lecture Room), and the Reading Room (behind the Library) (when not in use for conferences and committee meetings) of the National Academy of Sciences are available for the use of members to meet friends and to hold informal conferences. Those held in the Library should pay deference to the usual library regulations with regard to quietude.

Standard of time--As this program goes to press, there is uncertainty as to whether the District of Columbia will be on Eastern Standard or Eastern Daylight Saving Time at the time of the meeting. Judging from the past years, however, it is likely that Daylight Saving will be adopted.

ABSTRACTS OF PROGRAM PAPERS

SYMPOSIUM ON THE EARTH'S INTERIOR

(1) S. K. Runcorn (University of Cambridge, Cambridge, England) The Earth's Core--The modern view of the origin of the geomagnetic field associates it with motions in the liquid core of the Earth. This new approach, suggested by W. Elsasser, has led to a revival of interest in the main geomagnetic field and phenomena connected with it. The hypothesis of motions in the Earth's core not only accounts for the remarkably rapid changes in the geomagnetic field but also for the irregular fluctuations in the rate of rotation of the Earth.

E. C. Bullard has given convincing arguments for the belief that these motions in the Earth's core arise from thermal convection. It may easily be demonstrated that the motions are to a high degree dominated by the Coriolis forces arising from the Earth's rotation. Consequently model experiments on thermal convection under the influence of Coriolis forces are of great importance in understanding the physics of the Earth's core. Such experiments, done by R. Hide of the Department of Geodesy and Geophysics of Cambridge University, give rise to an interesting explanation of the westerly drift of the geomagnetic field, discovered by E. H. Vestine, and give patterns of motion involving jet streams, which are incidentally of remarkable similarity to the motions in the upper atmosphere.

The essentially two-dimensional motions which result from the dominance of the Coriolis forces are thought to supply a fundamental reason for the axial character of the geomagnetic field. Though much is known about the physical processes in the core relating to the geomagnetic field, the mechanism by which these motions set up electromotive forces are still obscure, though two lines of approach look promising. The first is that the motions maintain the field by a dynamo action and the second is that they set up temperature distributions which give rise to thermoelectric currents.

(2) Francis Birch (Harvard University, Cambridge, Mass.) Elasticity and Constitution of the Earth's Mantle--The principal facts contributing to modern ideas of the structure of the mantle will be briefly reviewed. Particular attention will be given to the problem of a physical interpretation of the seismic velocities and their variations with depth, following a method discussed in detail in a recent paper by the author in the *Journal of Geophysical Research* (Elasticity and constitution of the Earth's interior). The principal conclusions are (1) that the mantle as a whole is not homogeneous; (2) that there may be a reasonably homogeneous layer between the depths of 900 and 2900 km, consisting of high-pressure phases, presumably of the composition of a ferromagnesian silicate; (3) that gradual changes of composition, of the proportion of high pressure phases, or both, take place in a transitional layer between the depths of 200 to 900 km. Discovery of the nature of this transitional layer is considered to be of crucial importance for dynamical geology and petrology.

(3) J. Verhoogen (University of California, Berkeley 4, Calif.) Petrological Evidence on the Temperature Distribution in the Mantle of the Earth--From the maximum observed temperature of lavas and their composition it is inferred that basaltic magmas are formed by partial melting of mantle material at a depth less than 150 km and at an initial temperature less than 1400° C. This suggests that the temperature at the core boundary normally does not exceed 2400° C. Rising material at this initial temperature would have at 150 km depth a temperature sufficiently greater than the melting point at that depth to allow partial fusion. Temperature at the core boundary probably fluctuates, in space and time, between this maximum value of 2400° required to initiate convection and a minimum temperature of about 1300° corresponding with the end of a convectional overturn. The superadiabatic gradient required to overcome fundamental strength and viscosity would approximately equal the adiabatic gradient itself.

GENERAL ASSEMBLY LECTURE

Roger Revelle (Scripps Institution of Oceanography, University of California, La Jolla, Calif.) Preliminary Report on the Capricorn Expedition to the South Pacific--In this preliminary account made shortly after the return of the Expedition, a summary will be made of the field results including seismic refraction profiles, magnetic measurements, bathymetric surveys, measurements of the heat flow through the sea floor, radiosonde and other meteorological observations, coring and dredging of bottom sediments and rocks, studies of bottom water and other oceanographic, hydrologic, and geologic observations of the islands and the waters of the South Pacific. This Expedition was made to study the basin of the deep Pacific in its broadest aspects, paying particular attention to the Tonga Deep. The route passed Hawaii, the Marshall Islands, the Fiji Islands, the Samoan Islands, and the Marquesa Islands. The Expedition returned to San Diego in February 1953.

SECTION OF GEODESY

(1) Arthur S. G. Grant (Meteorological Division, Department of Transport, Ottawa, Canada) Notes on the Atmospheric Refractive Index in Canada from Aircraft Meteorological Soundings--Calculations of the atmospheric refractive index for radio waves were made from aircraft soundings over a large area of northern Canada in connection with the 1952 season of the shoran survey. A comparison is made between the results and the N.A.C.A. standard atmosphere with 60 pct relative humidity.

(2) John C. Duecker (Pennsylvania State College, State College, Pa.) Gravity Traverse in Northeastern Pennsylvania--A gravity traverse was made in northeastern Pennsylvania beginning near Millerton, in the Tioga area, extended south to Columbia Cross Roads, then east, following roads roughly parallel to the Pennsylvania border, to a point about a half-mile below Stockport Station on the Delaware River. The data taken along the traverse revealed a gravity profile with two significant features: a local anomaly of about 15 mgals over a distance of eight miles near the town of Montrose; and a regional Bouguer gravity increase of 70 mgals between Milan and Stockport, a distance of 65 mi.

(3) Stephan Thyssen-Bornemisza (Hotel Nacional de Cuba, Havana, Cuba) Development of a New Technique for Measuring the Vertical Gradient of Gravity--A new technique for measuring the anomalous vertical gradient of gravity by the use of gravimeters has been developed. The new technique is based on the analytical investigation of gravimeter errors on the one hand, and on a rotating system for the displacement of the gravimeters in the vertical direction on the other. The whole equipment is mounted on a trailer and measurements in the field are possible at an accuracy of about $\pm 1 \times 10^{-8}$cgs.

(4) Peter Hidnert and Richard K. Kirby (National Bureau of Standards, Washington 25, D. C.) A New Method for Determining Coefficients of Linear Thermal Expansion of Invar Geodetic Surveying Tapes--In this method an invar tape is heated to constant temperatures by passing direct electric current through it while the ambient temperature is held constant. Observations of changes in length versus electrical resistance of the tape are taken with micrometer microscopes and a potentiometer method, respectively. The temperature changes of the tape are determined from the changes of resistance and the temperature coefficient of resistance. The latter is obtained from observations of resistance versus temperature or from a relationship, derived by the authors, between temperature coefficients of resistance and mass resistivities. Coefficients of linear thermal expansion determined by this method from 15° to 35°C are in good agreement with those obtained by the method used previously at the National Bureau of Standards. With the new method the observers are not subjected to widely different ambient temperatures and the time required for the determinations is considerably reduced.

(5) J. A. O'Keefe (Army Map Service, Washington 25, D. C.) The Isoparametric Method of Mapping one Ellipsoid on another--Geodetic positions can be transferred from one ellipsoid to another by calculating x, y coordinates on some standard projection for the first ellipsoid, and then, regarding the x, y coordinates as identical on the two ellipsoids, reversing the computation using the constants and tables appropriate to the second ellipsoid. It is shown that the distortions introduced in this way are proportional to the distortions of the projection used for calculating the x, y coordinates; and that the ratio of proportionality is equal to the fractional change in the Gaussian curvatures.

(6) C. H. Ney (Geodetic Survey of Canada, Ottawa, Canada) Geographical Positions from Stellar Azimuths--A method is developed whereby latitude, longitude, and azimuth are deduced simultaneously from azimuth observations on three or more stars. For best results, the observations from 15 or 20 stars are combined in a least-squares solution. For each observed star, there is set up an observation equation of the form $x\,(d\phi) + y\,(d\lambda) - (dA) + \ell = 0$, where x and y are computed coefficients, ℓ the absolute term, and $(d\phi)$, $(d\lambda)$, and (dA) are the corrections to assumed values of the latitude, longitude and azimuth. Approximate values of the coefficients (x) and (y) are given in two short tabulations. The sharpness of the solution of the observation equations depends on the suitable choice of stars selected for observation. The discussion includes the choice and identification of stars and the computation of a numerical example. Using the most favorable selection of stars, geographical positions correct, astronomically, to about one-half a second of arc may be obtained by this method.

(7) T. J. Kukkamäki (Finnish Geodetic Institute, Helsinki, Finland, and the Mapping and Charting Research Laboratory, Ohio State University, Columbus, Ohio) Results obtained by the Finnish Solar Eclipse Expeditions, 1947--In 1947, the Finnish Geodetic Institute sent two expeditions to

observe the total solar eclipse; one to Brazil, the other to the Gold Coast. These expeditions used specially constructed cameras which had been designed for solar eclipse recordings and featured a smoothly moving film (as contrasted to the jerky movement of film in commercial cameras). Both expeditions were successful. The evaluation of their films gave the distance between two observation places with an accuracy of ±94 m. This error was mainly due to the prevailing poor knowledge of the profile of the Moon. When better values for the profile are available it is expected that the error will be reduced to about half its present size.

SECTION OF SEISMOLOGY

(1) Paul Lieber (Rensselaer Polytechnic Institute, Troy, N. Y.) On Wave Propagation in Visco-Elastic Materials--In earlier work a theory was developed for calculating the wave motion resulting from the application of a pressure pulse to the interior surface of a cavity situated within an infinite, homogeneous, isotropic, visco-elastic medium. On the basis of this theory numerical calculations giving the displacement relative to the cavity wall at a particular time were carried out. In the paper abstracted here a pressure-time pulse defined by a function of the form $P(t) = P_\alpha e^{\alpha t}$ was applied to the cavity wall and a solution to the differential equations of motion for the same boundary conditions used in the entire paper was then obtained. This new pulse form was selected for the purpose of providing a more realistic analytical representation of an actual explosion. In so doing, it was found that any pressure-time disturbance having this form would satisfy the differential equation and the boundary conditions for any and all values of the parameter α. Consequently, it is possible to represent a pressure-time pulse of arbitrary form by superposing individual pulses of the above form corresponding to different values of α. Furthermore, as the theory shows that the rate of attenuation of such a disturbance depends upon α, it follows that there is selective absorption. Accordingly, an arbitrary wave which is constructed by superposing component disturbances of the above form, will be distorted during the propagation. Thus, the freedom which the theory allows in selecting the numerical values for α implies that real pulses of any duration can be reasonably approximated by this method of superposition.

(2) Charles B. Officer, Jr. (Woods Hole Oceanographic Institution, Woods Hole, Mass.) The Refraction Arrival in Water-Covered Areas--A solution is given for the refraction arrival in water-covered areas in terms of the evaluation of a branch line integral for an impulsive point source. The physical significance of the mathematical solution is discussed, and experimental verification of the theoretical predictions is presented. The character frequency and range dependence of the refraction arrival agree with theory. Using the results of this theory and the conventional interpretation techniques for refraction seismograms, it is possible to determine the velocities and depths of the refraction horizons from the record of a single receiver. From the frequency of the refraction arrivals the depth of water and the velocity of sound in water the velocities of refraction horizon can be determined. Then, from the travel times the depth of the horizons can be computed. This method could be of importance in reconnaissance measurements of geologic structure over the continental shelves.

(3) William L. Donn (Dept. of Geology, Brooklyn College, and Lamont Geological Observatory, Columbia University) Direction Studies Using Microseism Ground-Particle Orbits--A large number of storm microseisms have been studied on Palisades records, using both statistical and individual wave analyses. The results show Rayleigh-wave properties for the microseisms studied. Ground orbits were constructed for microseisms generated both in restricted cold-front zones on the continental shelf and in distant oceanic cyclonic areas. Using orbits in the horizontal plane, nearly perfect direction correlations were obtained for microseisms generated on the shelf and very poor correlations for microseisms generated beneath distant ocean storms. A significant propagation difference is thus demonstrated for microseisms generated on opposite sides of the continental edge. Very good accuracy was also obtained from a similar study of R_g having a continental origin and with periods in the microseism range. Further, since poor direction correlations exists between epicenter and orbit alignment for short-period Rayleigh waves from ocean shocks, a strong similarity with microseisms is suggested.

(4) Frank Press and Maurice Ewing (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) Performance of Columbia Long-Period Vertical Seismograph--Features of the barometrically compensated, overdamped Columbia vertical seismograph with To=15 sec, Tg=90 sec, are described. Body waves often record with long-period components not evident on other seismographs. Shear waves, especially those multiply reflected, record as well or better on the new vertical than on Galitzin-type horizontals. Mantle Rayleigh waves up to order R15 representing waves with periods up to 480 sec and paths with as many as seven circuits of the Earth were recorded for the first time. Record loss due to microseismic storms is rare.

(5) Henry F. Birkenhauer (John Carroll University, Cleveland, Ohio) Seismic Vibrations in Machine Tools--Ground-borne vibrations from forging hammers can cause spoilage in the operational cycle of precision machine tools. A method of estimating the possibilities of damage from measurements of relative displacements in such machines and a technique of testing by means of vibration generators are described.

(6) Jack Oliver, Frank Press, and Maurice Ewing (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) Crustal Structure of the Arctic Regions from the Lg Phase--Previous studies of the Lg surface wave indicate that it is recorded only when the crustal structure along the entire path is continental. This fact is utilized to explore the Arctic Regions. Water-covered areas over which Lg propagates include Hudson Bay, the Barents Sea, and portions of Baffin Bay, Davis Strait, and the Greenland Sea. Lg is cut out by parts of the Arctic Ocean, the Beaufort Sea, the Okhotsk Sea, the Laptev Sea, the Norwegian Sea and the Greenland Sea.

SECTION OF METEOROLOGY

(1) Gilbert N. Plass (Dept. of Physics, Johns Hopkins University, Baltimore, Md.) The Carbon Dioxide Theory of Climatic Change--Some of the numerous theories of climatic change will be discussed. The important question of which one or combination of factors has largely controlled the climate can be answered only by quantitative calculations. We have re-examined the effect of CO_2 variations on the climate. Our calculations make use of the latest experimental results and take account of the variations in line shape at different pressures. Our results show, for example, that a 50 pct increase in CO_2 concentration would increase the surface temperature 2.2° C. Because of the many factors that influence the CO_2 concentration in the atmosphere, it seems almost certain that changes considerably larger than 50 pct have occurred during the Earth's history. The CO_2 effect has been considerably underestimated in recent years because (1) of neglect of the pressure effect; (2) the CO_2 lines far from the band center which give the largest contribution were largely neglected; (3) the shielding influence of the H_2O lines was overestimated. It appears that moderate CO_2 variations can have an important effect on climate and that this is at least one of the primary factors that must be considered in discussions of climatic change.

(2) Ronald L. Ives (Cornell Aeronautical Laboratory, Buffalo, N. Y.) Early Wisconsin Winds in Central Utah--Detailed studies of the embankments, terraces, bars, and channels associated with the bed of the Gilbert River in central Utah give a very clear picture of currents in a part of Lake Bonneville during the Bonneville-Provo Stage, tentatively placed in early Wisconsin time. Comparison of these structures with similar features of modern Great Salt Lake, and application of present-day meteorological data to conventional hydrological theories, indicate that the source of the dynamic wind (S^2T maximum), during the Bonneville-Provo stage, was in the northwest octant, as it is today in the same area. Relative size of transported rock fragments suggests, but does not conclusively demonstrate, that ancient winds were considerably stronger than those in the same area today.

(3) Christian E. Junge (Air Force Geophysics Research Directorate, Cambridge, Mass.) A Contribution to the Question of the Chemical Composition of Atmospheric Nuclei--On the basis of measurements of the complete size distribution of the atmospheric condensation nuclei it is attempted to show that the maritime component is restricted to particles greater than about 0.8 μ in radius. New investigations of the chemical composition of the particles between 0.2 and 0.8 μ radius show that these nuclei consist mainly of ammonium sulfate, not only over the European continent but probably over the most parts of the world. This is confirmed by electron diffraction measurements. The probable process of formation is discussed.

(4) C. H. Keith and A. B. Arons (Woods Hole Oceanographic Institution, Woods Hole, Mass.) The Growth of Sea-Salt Particles by Condensation of Atmospheric Water Vapor--Measurements of the time rate of growth of sea-salt particles of mass between 10^{-9} and 2×10^{-8} grams have been made when the particle was suddenly shifted from an environment of dry air to one of relative humidity between 80 and 100 pct. The measurements are found to be in agreement with growth times predicted by an approximate equation similar to that developed by Howell in 1949. The growth rate is observed to be independent of the ventilation at air speeds less than 30 to 40 cm/sec. The growth equation was reintegrated with variable temperature and humidity conditions corresponding to rates of rise observed in the atmosphere. The curves thus obtained approximately trace the growth of sea salt particles on rising from sea surface to cloud base.

(5) A. H. Woodcock and D. C. Blanchard (Woods Hole Oceanographic Institution, Woods Hole, Mass.) Sea Salt in the Air, and in the Rains of Hawaii--Salt particles produced at the surface of

the sea play a significant role in meteorology. Numerous measurements have been made of the size distribution of these particles in the clear air in Hawaii. The number and size of raindrops and the salt content of rain waters within clouds have also been determined. Studies of these measurements are presented, and the results are shown to support the hypothesis that the large salt particles become raindrops.

(6) C. E. Anderson and H. Glazer (Air Force Geophysics Research Directorate, Cambridge, Mass.) The GRD Adiabatic Expansion Chamber: A New Tool for Cloud-Physics Research-- A description of the design and performance of a serve-mechanism controlled cloud chamber is presented. This equipment, which was built especially to achieve slow expansions, offers unique possibilities for quantitative research on problems in the field of condensation physics. The formation and growth of clouds and fogs can be studied for the influence of such variables as: nature and size spectrum of nuclei, rate of cooling, rate of expansion, and coagulation. The results of some experiments are shown as samples of the research planned utilizing this equipment.

(7) H. W. Dubach and W. E. Maloney (U. S. Navy Hydrographic Office, Washington 25, D. C.) A Discussion of the Meteorological and Oceanographical Conditions Resulting in the Storm Disaster in the Irish and North Seas on February 1, 1953--The chronological sequence of meteorological and oceanographical conditions culminating in the disastrous storm tides on February 1, 1953, in the Irish and North Seas are reviewed. Each element taking part in the transfer of energy from the storm to the shore via the sea is discussed. It is shown that the time of arrival, onshore, of the various energy carriers gives a clue to the reason for the extensive damage in certain areas.

(8) R. E. Burns, L. B. Bertholf, and C. C. Bates (U. S. Navy Hydrographic Office, Washington 25, D. C.) The Destructive Storm Surge of March 18, 1952 Along the Gulf Coast; I, Oceanographic Aspects; II, Meteorological Aspects--A storm surge formed in the Gulf of Mexico on March 18, 1952 which moved southwards along the coast of Mexico as far as Progeso and eastwards along the United States coast as far as Key West, Florida. The initial wave crest reached its maximum height in the vicinity of Southwest Pass, Mississippi River where the surge advanced as a breaking wave and caused considerable damage. A second crest about three hours later did not break, however. An attempt is made to explain the double crest of the surge and to relate it to existing meteorological and oceanographic conditions.

(9) Gerhard Neumann (Dept. of Meteorology and Oceanography, New York University, New York, N. Y.) Some Relationships between the Atmospheric Circulation and Sea Surface Temperatures--Certain meteorological anomalies indicate the importance of temperature of the underlying water surface, especially of its anomalies or fluctuations, not only in large, well-known regions of upwelling water along the coasts, but also in locally limited areas in the open sea. It has been found that sea surface temperature anomalies appear and disappear almost simultaneously over wide regions of the ocean. They tend to occur with opposite signs at the same time in different areas, and in most cases the contrast between the northwestern and southeastern or eastern parts of the North Atlantic is striking. The observed temperature anomalies seem to be closely related to fluctuations of the atmospheric-hydrospheric circulation system, and the question for the causes of these anomalous temperature variations is discussed.

(10) Basil W. Wilson (Dept. of Oceanography, A and M College of Texas, College Station, Texas) Generation of Long Period Seiches in Table Bay Harbor, Cape Town, by Barometric Oscillations--Table Bay Harbor, Cape Town, South Africa, is shown to be subject to two wave phenomena resulting from seiches in Table Bay and from smaller oscillations peculiar to the harbor itself. The lower frequency seiches of the Bay when they attain to appreciable amplitudes are usually unaccompanied by swells such as induce seiches within the harbor basins. Investigation of a possible seismic origin for these longer seiches showed that they could not derive from this source, but a positive correlation was established between their occurrence at Table Bay and Port Elizabeth and the simultaneous existence of barometric oscillations in the overlying air mass at both centers. Attention is drawn to the inherent dangers from the powerful fluxing of water through the entrances to harbors from this cause; the frequency of these effects at Cape Town has been found to vary from one or two to about 15 occasions per year. Consideration of specific examples of the seiche phenomenon and the local meteorological conditions emphasises the importance of the directional approach of the barometric oscillations. Southeast winds from the land, although inducing barometric oscillations, as a result of standing wave formation in the lee of Table Mountain, fail to generate seiches. The suggestion is advanced that the seiches derive from the aerial commotion arising out of the coalescence of frontal depressions near the extremities of such fronts.

(11) E. B. Callaway (U. S. Navy Hydrographic Office, Washington 25, D. C.) Ice-Thickness Forecasting as Applied to Baffin Bay and Davis Strait Area--The derivation of a forecast formula

for ice-thickness prediction based upon a solution of Fourier's heat-transfer equations in terms of the oceanographic and meteorological parameters involved is described. An application of the method is made to the forecasting of ice thickness, and the first appearance of ice from data collected by ice breakers in the Baffin Bay - Davis Strait area.

(12) Dale F. Leipper (Dept. of Oceanography, A and M College of Texas, College Station, Texas) The Forecasting Problem in Oceanography--The development of oceanographic forecasting methods will greatly strengthen and extend the program of cooperation between oceanography and meteorology. This development at the present time has progressed to a stage roughly equivalent of that which existed in meteorology in the years 1910 to 1920 when the first large scale systematic exchange of synoptic information was initiated and when the first extensive programs in research and training were established. Progress in oceanographic forecasting(for example, forecasting fluctuations in ocean currents, sea-ice conditions, ocean waves, plankton and fish populations, sea temperature, underwater sound velocity, transparency of sea water) will depend heavily upon the science of meteorology first because of the similar nature of many of the problems involved and second, because it has now been demonstrated clearly that many oceanic fluctuations may be traced directly to weather phenomena.

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

(1) Zdenko Frankenberger (Gulf Research and Development Co., Pittsburgh, Pa.) The Compensation Method for Absolute Measurement of the Terrestrial Magnetic Field--Information concerning a new type of absolute magnetic instrument is presented which in comparison with the older types has the following principal advantages: (a) No permanent fields are used except in the zero-galvanometer. (b) The only correction is due to the temperature. (c) The zero-method is used. (d) All three elements are measured with the same instrument so that all results are affected by the same eventual errors.

The method is based on interaction of two Helmholz coils, a small one deflecting in the Earth's magnetic field and a large one compensating the field's component which is parallel with the axis of the coil. Current and number of turns are controlled. The component of H parallel to the axis k is given

$$H_k = -(32\pi E_3/5 \quad \sqrt{5}\, a\, R_4)\, n/[1 + N(\nu + \tau/1000)]$$

(2) Jules Aarons (Upper Air Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Cambridge, Mass.) and Martha Henissart (Wentworth Institute, Boston, Mass.) Low-Frequency Magnetic Noise in the Range 1/2 to 20 Cycles per Second--Continuous recordings of low-frequency magnetic fluctuations have been made with high-gain equipment designed for this purpose. The frequency range is one half to twenty cycles. Sites were chosen for low interference characteristics and recordings maintained for eighteen months. Two sites were instrumented and kept in simultaneous operation for an overlap period of several months. The existence of low-frequency magnetic storms is of more than local origin. Data analysis includes daily means, diurnal variations, and correlation coefficients between low frequency noise and other geophysical phenomena. A significant correlation exists between low-frequency noise and solar-radio noise on 200 megacycles. The occurrence of a twenty-seven day figure in the computations would indicate some relationship to the rotation period of the Sun. Further analysis however is necessary before any specific causation can be attributed to this phenomenon.

(3) Elwood Maple (U. S. Naval Ordnance Laboratory, White Oak, Silver Spring 19, Md.) The Short-Period Variations of the Horizontal Component of the Geomagnetic Field at Point Barrow, Alaska--Variations in the horizontal component of the Earth's magnetic field were measured at Pt. Barrow, Alaska, in July and August of 1950. The amplitudes of the variations were approximately inversely proportional to their frequencies. The average of the three largest signals in each three hour period decreased from about 20 gammas at 0.0075 cps to about 0.5 gammas at 1 cps. The amplitudes of the variations correlated closely with the three-hour K indices of the Pt. Barrow observatory of the U. S. Coast and Geodetic Survey. Diurnal trends will also be discussed. The voltage induced by the variations in a search coil was recorded on magnetic tape. The records were played back at increased tape speed, and the resulting signal was analyzed electrically by means of an amplifier having ten narrow band-pass channels covering the desired frequency range. The output of five of the frequency channels were examined in detail; the other five channels indicated no appreciable departures from the trends thus obtained.

(4) L. W. Morley (Geological Survey of Canada, Ottawa, Canada) Problems of Aeromagnetometry within the Auroral Zone--Aeromagnetic surveying within the auroral zone is complicated

by the high frequency of occurrence of large magnetic disturbances. Whereas corrections for the time variations of disturbance fields could be made using data obtained from a ground station located centrally within the survey area, the areal extent over which such corrections would be sufficiently accurate is not known. Magnetic disturbance data obtained from two simultaneously operated ground stations placed at first one hundred and thirty and then eighty-seven miles apart within the auroral zone are presented to show that such correction would be seriously in error for separation of this order between ground and air stations.

(5) S. K. Runcorn (University of Cambridge, Cambridge, England) The Electrical Conductivity of the Earth's Mantle--The rapid rise in electrical conductivity at depths of 700 km in the Earth's mantle, inferred by S. Chapman and his collaborators from a study of the transient variations of the geomagnetic field, may be well explained on the hypothesis that the process of intrinsic semiconduction is of importance in this region. H. Hughes of the Department of Geodesy and Geophysics, Cambridge University, has demonstrated the various semi-conduction processes occurring in olivine and similar minerals and has shown that the results fit in well quantitatively with the observational data referred to above. An indirect method of estimating the effect of pressure on the process of intrinsic semi-conduction has been attempted and does not appear to alter the view that the rapid rise in conductivity is, in essence, a temperature effect. From this work estimates can be made of the electrical conductivity of the lower part of the mantle, which agree with estimates inferred from the spectrum of the secular variation of the geomagnetic field and the explanation of the irregular fluctuations in the length of the day.

(6) Sydney Chapman (Queen's College, Oxford University, Oxford, England, and Geophysical Institute, University of Alaska, College, Alaska) and Masahisa Sugiura (Geophysical Institute, University of Alaska, College, Alaska) The Average Storm-Time Variation of the Electric Current Systems of Magnetic Storms--The electric current systems of 40 moderate magnetic storms as a function of storm time are derived from the average features of magnetic storms previously obtained by one of the authors (S. Chapman, 1918, 1927, and 1952).

(7) Edwin J. Chernosky (Air Force Geophysics Research Directorate, Cambridge, Mass.) On a Quasi-Centennial Variation of Sunspot Number--Studies of solar activity are usually made employing monthly and annual means of the Wolf daily relative sunspot number. These means inherently smooth out cyclic variations of about a month or a year or less, respectively. In this study, means of longer periodicities are computed in order to eliminate the corresponding cyclic variations. These are means of undecennial cycles, and 22-year periods. The long period variation for the 1749-1951 data shows two maxima and two minima with a third and high maximum developing at or near the present epoch. The time separation of successive minima or maxima is from 60 to 110 years. This quasi-centennial variation and simple tests indicate an interdependence of activity levels of successive cycles not contemplated in the usual 'outburst' theory. Each eleven-year cycle can be considered as an 'outburst' however whose magnitude is dependent upon the secular level of activity. The predictability of later cycles is thus related to the predictability of the quasi-centennial variation. Features of mean sea level, permafrost, glacier movements, or other geophysical phenomena having similar long period variables may have a relation to this solar change. Any coincidence with the present high secular levels of activity of meteorological parameters, or resulting conditions, relatively unknown for eight or ten decades also merits attention.

(8) H. Freeborn Johnston (Central Radio Propagation Laboratory, National Bureau of Standards, Washington, D. C.) List of Magnetic Observatories and Thesaurus of Values--At the Ninth General Assembly of the International Union of Geodesy and Geophysics, held at Brussels, Belgium in 1951, the Association of Terrestrial Magnetism and Electricity established a Committee on Thesaurus of Annual Values at Geomagnetic Observatories. The tabulated values are those that have been received during the 12 months ending April 30, 1953. In general they are for current years though corrections of earlier published values are included. The excellent cooperation of observers-in-charge makes the table possible. Quite a number of officers responsible for reduction of the data have even supplied values for the year 1952.

(9) L. M. Branscomb (National Bureau of Standards, Washington, D. C.), R. J. Shalek, and T. W. Bonner (Rice Institute, Houston, Texas) Intensity Distributions in Nitrogen Bands Excited in Auroras and by High Energy Protons and Hydrogen Atoms--Nitrogen negative and second positive band spectra have been excited by 100-kilovolt protons and hydrogen atoms from the Rice Insitute van de Graaf accelerator. The intensity distributions in the vibrational bands are compared with spectra produced in controlled laboratory experiments by canal rays and electron impact, with auroral spectra, and with results of theoretical calculations. Excitation of second positive bands by high energy neutral hydrogen atoms and of the negative bands by both neutral hydrogen

and protons show the expected marked increase in the rate of population of high vibrational states. Theories for the excitation of the auroral bands are discussed in the light of these results and theoretical considerations.

(10) Sydney Chapman (Queen's College, Oxford University, Oxford, England, and Geophysical Institute, University of Alaska, College, Alaska) Notes on Auroral Geometry and Optics; I, To Locate an Elevated Point Viewed from Two Ground Stations in the Same Diametral Plane--A simple graphical method is explained for obtaining the height and location of a point P from its elevations e and e' as observed from two points Q, Q' on the Earth's surface, in the same diametral plane as P.

(11) Joseph C. Cain (Geophysical Institute, University of Alaska, College, Alaska) Auroral Radio-Echo Table and a Diagram for a Station in Geomagnetic Latitude 56°--A method described in a recent paper by Chapman is used to calculate a table and construct curves for the points in space that will return a radio wave normally from auroral ionized sheets lying along lines of force of the geomagnetic field to a transmitter in geomagnetic latitude 56°

(12) Rita C. Sagalyn and Gerard A. Faucher (Air Force Geophysics Research Directorate, Cambridge, Mass.) Relation between Electrical and Meteorological Parameters in the Free Atmosphere--The vertical distribution of electrical conductivity, large ion content, temperature, pressure, and relative humidity has been measured in the free atmosphere with instruments installed in a B-17 aircraft. Over 25 flights have been conducted in fair weather in the altitude range 1000 to 15,000 ft on selected flight paths in Texas and New England. The results show that in fair weather over continental areas the troposphere is divided into two layers with distinct electrical and meteorological characteristics. The lower layer, which originates in the daily cycle of turbulence, is characterized by high large ion content, relatively high humidity, with correspondingly low electrical conductivity. The upper boundary of this layer has been found to vary between 4000 and 8000 ft from day to day. Above this boundary the large ion content and humidity decrease to very low values; the electrical conductivity increases in accordance with relations previously determined for the free atmosphere. The constant pressure altitude records clearly show a direct correlation between temperature, humidity, and large and small ion variations.

(13) Samuel C. Coroniti and Eldon Heaton (Air Force Geophysics Research Directorate, Cambridge, Mass.) The Electrical Conductivity of the Atmosphere over the Pacific Ocean--The electrical conductivity of the atmosphere was measured over the Pacific Ocean. The measurements were made at altitudes of 12,500, 17,000, and 21,000 ft and between geomagnetic latitudes of 22° and 45°N. The value of q computed from the measured conductivity values agrees very well with those derived from cosmic-ray data.

(14) Serge A. Korff (New York University, University Heights, New York 53, N. Y.) Effects of the Cosmic Radiation on Terrestrial Isotope Distribution--The effects of the cosmic radiation in building up and altering the terrestrial isotope distribution are computed. The most striking effect is the production of radiocarbon, but as this beta decays to nitrogen it does not alter the distribution permanently. The second important process is the production of tritium, and its subsequent decay into helium three. The problem is discussed quantitatively. Finally it is shown that several other possible reactions do not contribute in an important degree to the existing distribution.

(15) Bernard J. Dunn (Fordham University, New York, N. Y.) The Use of Square Voltage Waves to Determine the Mobilities of Gaseous Ions--A proposed method of investigating ionic mobilities is described in which a square voltage wave is applied to an ionization chamber. The chamber is so designed that the electric field is uniform. The current collected alternates in direction and the average value of either unidirectional current is measured separately by a parallel circuit containing two diodes, the current passing alternately through one or the other diode. The theory for the case of ionization produced only in a thin layer of gas next to the electrode indicates that the average unidirectional current should decrease linearly with increasing frequency until a cutoff is reached. From a current versus frequency plot, it should be possible to determine the mobility of either the positive or negative ions. Discontinuities in the slope of the curve should indicate the presence of several mobilities, and from this it should be possible to estimate the fraction of the total ionization that is due to ions of the various mobilities. Experiments with various gases at various pressures are contemplated.

(16) Sanford C. Gladden (National Bureau of Standards, Washington 25, D. C.) Procedures Employed in the Quality Control of Ionospheric Data by the National Bureau of Standards--The Ionospheric Data Quality Control Group of the Upper Atmosphere Research Section, Central Radio Propagation Laboratory, has as its primary function the examination of data received from 21 field

stations including associated laboratories. This group has the task of determining whether the stations submitting the data have properly scaled the records. The check of the records may provide a clue to the station engineer as to possible operating errors which may impair the quality of the records. Slides are shown to illustrate the type of records examined, and to indicate results of interstation comparison. Stations separated by not more than four degrees of geomagnetic latitude are compared graphically as regards monthly medians of the various characteristics. Discoveries of operating difficulties which had escaped observation for several months are described. A type of scaling error discovered by graphical comparison of stations is related.

(17) C. R. Wilson (Geophysical Institute, University of Alaska, College, Alaska) Notes on Auroral Hydrogen and the Evolution of an Auroral Display--Spectrograms have been taken to show the spectral changes through auroral displays during the winter of 1952-53. Exposures were begun prior to an expected display and continued throughout the display. Observations were taken both along and perpendicular to incoming proton streams. Measurements of the intensities of the hydrogen lines have been made and preliminary results are presented as a function of the auroral display time.

SECTION OF OCEANOGRAPHY

(1) Kenneth N. Granthem (College of Engineering, University of California, Berkeley, Calif.) Wave Run-up on Sloping Structures--Relationships have been developed from laboratory experiments which show the effect of side slope, wave steepness (H/L), relative depth (d/L), and the structure porosity on wave run-up. Maximum wave run-up occurs, for the range of angles examined, at approximately 30 degrees. As the wave steepness (H/L) increases, the wave run-up increases, and as the relative depth parameter (d/L) decreases the wave run-up increases. The wave approach was restricted to the direction perpendicular to the axis of the structure.

(2) R. L. Wiegel, D. A. Patrick, and H. L. Kimberley (University of California, Berkeley, Calif.) Surf Conditions and Beach-Profile Records for Santa Margarita Beach, Oceanside, California, for 1949--For a period of approximately one year the beach at the mouth of the Santa Margarita River (just north of Oceanside, California) was surveyed at two-week intervals while, at the same time, continuous wave recordings were made. It is believed that these data are the most complete available with which to correlate ocean beach changes with varying wave conditions.

(3) D. A. Patrick (University of California, Berkeley, Calif.) Comparison of Beach Elevation at Limits of Backwash and Uprush with U. S. Coast and Geodetic Survey Tide Predictions on Several Pacific Coast Beaches--Establishing a datum plane for elevations is very important for studies in amphibious oceanography. Such a plane can be used as a basis of reckoning for hydrographic surveys, beach profiles, beach erosion studies, and wave and surf predictions. Tide predictions are published by the U. S. Coast and Geodetic Survey for 150 reference ports throughout the world along with tidal differences and constants for about 4400 additional stations. Tide stages can be obtained with reasonable accuracy from these tables. If a method can be found to locate tide level at a given time or times, a datum can be established at any beaches in the world near a published reference station. This report presents data from field measurements and attempts to correlate them with the tide predictions on several Pacific Ocean beaches.

(4) Charles L. Bretschneider and Robert O. Reid (Department of Oceanography, Texas A and M College, College Station, Texas) Changes in Wave Height Due to Bottom Friction, Percolation, and Refraction--In a paper in the Transactions in 1949, Putnam and Johnson have given expressions for the dissipation of wave energy by bottom friction based upon the Airy wave theory, and Putnam, also in the Transactions of 1949, developed a dissipative function for the effect of percolation in a permeable sea bottom. These authors made use of the energy dissipation functions to calculate, by successive approximations, the transformation of wave height resulting from the action of bottom friction, percolation, and a combination of these for a train of waves traveling into shallow water. In this paper, by making use of the dissipation functions presented in the cited papers, a direct, general solution of the problem of wave height transformation is developed. The solution of the problem presented here is direct in that it avoids the method of successive approximation, and is general to the extent that it incorporates the effect of refraction as well as friction and percolation. A formal solution of the problem is presented for the general conditions of bottom configuration encountered in the field. Evaluation of the wave-height changes for complex situations usually found in the field requires numerical integration; however, this procedure involves simple summations only. Exact solutions of the problem can be obtained for several special cases of interest. One of these is that of a flat bottom (constant depth), wherein one considers the effects of friction, percolation, and initial divergence of wave rays upon entering such a region. This

situation may be approximated for certain regions of the Gulf shelf where exceedingly small slopes are found. Another special case is that of a constant slope, considering bottom friction effect only. A third special case is that of a constant slope, considering percolation and refraction only. For all of these special cases, the formal solution can be integrated directly and the resulting formulas are presented here.

A combination of the solutions for friction only and for percolation only is developed which yields a very close approximation for the integrated effect of friction and percolation for a constant slope. Graphs have been prepared for the relationships between the pertinent dimensionless parameters in order to facilitate computations for a particular situation. Computations for typical examples of wave energy loss due to friction and percolation, using the methods proposed in this paper, are made and compared with the results computed by Putnam and Johnson. In addition an actual field example, wherein refraction is included, is worked out in order to illustrate the practicality of the method.

(5) Alfred C. Redfield (Woods Hole Oceanographic Institution, Woods Hole, Mass.) Interference Phenomena in the Tides of the Woods Hole Region--The relations of mean range of tide, time of high water, and time of slack water along Vineyard and Nantucket Sounds may be attributed to the interference of tidal waves entering the sounds from their opposite ends. Interference of the semidiurnal constituents is maximal in the neighborhood of Woods Hole where the great reduction of these constituents, relative to the diurnal constituents, results in a pronounced diurnal inequality in the range of successive tides at appropriate phases of the Moon. The tide-gage record at Woods Hole is distorted in form as a result of the development of shallow water harmonics combined with the reduction of the fundamental semidiurnal constituent by interference. The inequality in the duration of flood and ebb currents in Woods Hole Passage may be attributed to the effect of this distortion on the tide levels in Great Harbor.

(6) W. E. Maloney and R. E. Burns (U. S. Navy Hydrographic Office, Washington 25, D. C.) A Method for the Determination of the Natural Period of Enclosed or Semi-Enclosed Basins--The character of the forced tidal oscillations in an enclosed basin or of the oscillations in a semi-enclosed basin depends upon the relation of the forced oscillation to the natural period. Starting with the equation of forced simple harmonic motion, it is shown that the M_2/S_2 ratio is a function of the gravitational attraction of the Sun and Moon, and, the period of the principal lunar constituent (M_2), the period of the principal solar constituent (S_2), and the natural period of the basin. Using this relation and the average observed M_2/S_2 ratio of a basin it is possible to determine by a simple and rapid method the natural period of the basin. The natural periods of the Western Mediterranean Basin, the Eastern Mediterranean Basin, the Adriatic Sea, and the Bay of Fundy are derived by this method and shown to be in good agreement with previous determinations and tidal observations.

(7) W. Armstrong Price (Dept. of Oceanography, Texas A and M College, College Station, Texas) Energy Classification of Coasts and Shorelines--Relative values of marine energy and resistances of bottoms and shorelines with character of erosive tools present are used to explain degrees of coastal modification as shown by extent of shoreline simplification and development of a bottom profile of equilibrium across continental shelf. Quantitative values of bottom gradients and onshore winds agree with energy classification made for coasts of Gulf of Mexico. Stillstand of sea for 3000 years (plus an unknown length of time when sea last stood at same elevation) has given perfect, steep profile on high-energy/low-resistance coasts and lower, less perfect profiles on coasts of lower energy and higher resistances. The classification yields relative and some approximate time values for profile development (plus unknown time increment) and will permit correlation between shoreline characteristics and offshore oceanographic conditions as these become more fully known.

(8) Francis A. Richards (Woods Hole Oceanographic Institution, Woods Hole, Mass.) Oxygen-Density Relationships in Three Detailed Cross-Sections of the Gulf Stream--Redfield has found that there is a characteristic oxygen-density relationship in waters of the Sargasso Sea, and that in subsurface Caribbean waters the oxygen is characteristically lower than in Sargasso waters of corresponding density. This characteristic low oxygen-density relationship has been observed in Yucatan Channel and the Straits of Florida, but until recently there have been few oxygen samplings in this density layer in the Gulf Stream. Three detailed sections have now been made across the Gulf Stream, and water of Caribbean type oxygen-density was found concurrent with water of maximum velocities. Thus, the oxygen-density relationship appears more useful in identifying Caribbean water in the Gulf Stream than the salinity-temperature correlation. There is preliminary evidence that this criterion is useful as far east as the Grand Banks.

(9) Frank Chew (Marine Laboratory, University of Miami, Coral Gables, Florida) Results of Hydrographic and Chemical Investigations in the Region of the "Red Tide" Bloom on the West Coast of Florida in November, 1952--Eleven hydrographic stations were occupied in the Gymnodinium bloom area off Fort Myers, Florida, in November, 1952. At each station water samples were taken at three depths (surface, mid-depth, and near bottom). These data provide the basis for a three-dimensional description of the hydrographic environment where the phenomenon occurred. The current pattern in the area of investigation was more complex than is generally thought. There was an interplay of transient southwesterly and general northerly flows. The axes of the shallow water columns were tilted by wind traction; consequently, the vertical distribution of phosphorus was similarly affected. Regions of maximum total phosphorus were found to coincide with water of Gulf origin, while water with greater river influence contained regions of minimum total phosphorus. This pattern implies that the increased phosphorus content came not from the river runoff but from the open Gulf.

The total phosphorus changed but slowly with depth in a slanting water column, and areas of definite Gymnodinium bloom, while high in total phosphorus, did not coincide with areas of maximum total phosphorus, suggesting that the Gymnodinium bloom was only part of a general plankton bloom. The highest total phosphorus value found in the present investigations is more than ten times the normal value, but is considerably less than the maximum found in the 1946-1947 G. beevis bloom. Smith's suggestion of bottom leaching offshore may provide a mechanism for the increased total phosphorus observed. Graham's hypothesis of local concentration of Trichodesmium provides another possible mechanism if the algal concentration is effected offshore and a suggested sequence of events occur. Moore postulates an offshore surface convergence area where the swimming dinoflagellates are concentrated in the surface layer, which becomes the total water column as the whole convergence area is advected toward the shallow continental shelf. No proven explanation of the causes of the recurrent plankton blooms is as yet available.

(10) Louis A. Post (U. S. Navy Hydrographic Office, Washington 25, D. C.) The Role of the Gulf Stream in the Prediction of Iceberg Distribution in the North Atlantic--A 26-year correlation is made between the yearly frequency fluctuations of icebergs south of the 48th parallel and the pre-seasonal sea-surface current and temperature fluctuations of the Gulf Stream in the Straits of Florida and those of the Labrador Current three years later. Good agreement among these variables is attributed to (1) the immediate effect of the relative strength of the Gulf Stream in barring the southward flow of bergs, and (2) the effect that varying strength of the Gulf Stream has upon the volume of warm water that escapes to the north, the effect in turn upon the rate of transport of icebergs, and the potential number eventually to be carried into the shipping lanes. An iceberg prediction table is offered, making possible a prediction for the current year by using the Gulf Stream sea temperatures for March of this year together with the temperatures of three years earlier.

(11) Richard H. Fleming (Department of Oceanography, University of Washington, Seattle 5, Wash.) Activities of the Department of Oceanography, University of Washington, 1952--During the summer of 1952 the M.V. Brown Bear made several exploratory cruises off the Washington coast. Emphasis was placed on the GEK to determine the water movements. Sections normal to the coast, repeated traverses of a short section, and observations at an anchor station 350 miles off the coast, all show that variable currents are of greater magnitude than the average flow. Analyses indicate that the variable components are probably of tidal origin. Studies have been continued on the penetration of salt water into the lakes, and on submarine geology, chemistry, and physics of the water of Puget Sound. A program of plankton investigation has been initiated.

(12) W. C. Krumbein (Northwestern University, Evanston, Ill.) Statistical Designs for Sampling Beach Sand--Problems associated with sampling of beach sands involve questions of sample size, depth of penetration, sample spacing, and sampling for seasonal variation. These types of problems can be studied by analysis of variance techniques, in which experiments are designed to explore several of the relations at a time. As a result of the experiments, it is possible to decide at any selected level of probability whether significant variations are introduced by specific techniques. Moreover, relatively sound inferences may be made of the population characteristics of beach deposits. A series of sampling experiments conducted over the past several years is described and summarized in terms of observed variations which occur on Lake Michigan beaches. Two generalizations, which emerge from the work, are that most beach characteristics are normally distributed within limited areas of the beach, and that the berm is an important dividing line between differing populations of many beach attributes.

(13) Albert Ehrlich (Air Weather Service, U. S. Air Force, Washington, D. C.) Subsurface Density Inversions off Nantucket Island--Soundings taken south of Nantucket Island in the region

of the discontinuity between the Gulf of Maine outflow waters and the denser offshore water show density inversions in the middle levels. The inversions are correlated with the tidal period, but not with the diurnal period. Rayleigh's instability criteria and other methods are used to investigate the conditions under which such inversions can exist. An equation is derived to obtain current velocities at different levels throughout the tidal period from the surface tidal currents. Trajectories for each level indicate extensive overrunning of the lower layers by the upper layers during each tidal period. The magnitude of this overrunning is sufficient to reverse the slope of the discontinuity surface between waters of the Gulf of Maine and the offshore waters, and to cause the inversions observed. A comparison between the conditions off Nantucket Island and cases of instability in other parts of the Atlantic Ocean shows a basic dissimilarity between them.

(14) Allen H. Schooley (Naval Research Laboratory, Washington 25, D. C.) A Simple Method for Measuring the Statistical Distribution of Sea-Surface Slopes--A flash-photography technique for determining the statistical distribution of slopes and facet areas of wind-created waves will be described. The technique has been used successfully both in daytime and at night. Wave-slope-probability-density curves, as measured from the South Capitol Street Bridge on the Anacostia River, will be given for wind velocities up to 20 knots. The application of this technique to measuring wave slopes of the open sea from aircraft will be discussed.

(15) Wilbur Marks (Dept. of Meteorology and Oceanography, New York University, New York, N. Y.) Power Spectrum Analysis of Ocean Waves by the Use of Aerial Stereo-Photography--It is shown that the method of stereo pairs is the most practical way to obtain wave records which characterize the sea surface completely at any given place, on the shortest notice, and with the least hazard to personnel and property. The three-dimensional aerial photograph of the sea surface thus obtained is divided into N wave records spaced Δy feet apart. The N wave records are combined statistically into one wave record, and the power spectrum is then computed. A filter function which depends on N and Δy is defined. The filter function operates on the power spectrum in such a way that for proper choice of N and Δy, the waves whose directions are any other than that which is desired are eliminated. The power spectrum which results is composed of the energy of those waves which will travel in the desired direction.

(16) Gerhard Neumann (Dept. of Meteorology and Oceanography, New York University, New York, N. Y.) On the Energy Distribution in Ocean-Wave Spectra at Different Wind Velocities--Based on recent observations of the composite nature of wind-generated waves, and on theoretical reasoning, the spectrum of wave energy (distribution function) is derived for a continuous sequence of wave components with frequencies between 0 and ∞. Each spectrum has an optimum band at a frequency ν_{max}, where most of the spectral energy is concentrated. The position of this energy maximum is given by $\nu_{max} \cdot v = \sqrt{2/3}\, g$ (= constant) in fully developed sea at a given wind velocity v. The range of periods of wave components with a significant amount of energy, that is, the width of the spectrum, depends upon the wind velocity and the state of development of the composite wave pattern. The total amount of energy in ocean wave spectra at different wind and fetch conditions is derived from the distribution function. The results are presented in the form of power spectra for convenient use in practical wave forecasting.

(17) Willard J. Pierson, Jr. (Dept. of Meteorology and Oceanography, New York University, New York, N. Y.) An Interpretation of the Observable Properties of "Sea" Waves in Terms of the Power Spectrum of the Gaussian Record--The results of a basic paper in communication theory on the Mathematical Analysis of Random Noise by S. O. Rice are applied to the problem of defining the visual properties of ocean waves in terms of the power spectrum of the waves. On the basis of new results obtained by Neumann on the nature of wave spectra, many complicated properties of the waves are explained theoretically. It is shown that the average of the time intervals between successive crests as observed at a fixed point does not yield a "period" which is representative of the wave where most of the spectral energy is concentrated. It is shown that the formula $L = g\,T^2/2\pi$ does not apply to sea conditions and that the result of using the formula is wrong by about 40 pct. Finally a completely logical explanation of the period increase of ocean swell is given which eliminates the error which occurs when the "period" in the decay area is treated as if it increases indefinitely.

(18) R. W. James (Dept. of Meteorology and Oceanography, New York University, New York, N. Y.) Concerning the Power Spectrum of Ocean Waves--A method of wave forecasting based upon the power spectrum of the waves is briefly reviewed. A detailed description of the graphs and tables used explains the procedure followed in this type of forecasting. A numerical example, involving generation and decay of waves in an East Coast storm, is discussed.

(19) Koji Hidaka (Dept. of Oceanography, Texas A and M College, College Station, Texas) Theoretical Studies on the General Circulation of the Pacific--A theory is determined for the general circulation of the Pacific induced by the semi-permanent wind system prevailing over this ocean. The solution is obtained in terms of the current velocity itself. The effect of the meridional variation of the Coriolis forces and the coefficients of both horizontal and vertical mixing are taken into account. The solution for the stream lines are worked for different levels including the surface.

(20) Koji Hidaka (Dept. of Oceanography, Texas A and M College, College Station, Texas) A Contribution to the Theory of Upwelling and Coastal Currents--A theory of upwelling and coastal currents induced by longshore and offshore winds is determined, taking the effects of Coriolis forces and the horizontal and vertical mixing into account. In the first place, it is shown that an upwelling circulation can be caused in the vertical plane perpendicular to the coast by a wind blowing parallel to the coast in such a manner that, in the northern (southern) hemisphere, the coast is on the left-hand (right-hand) side of an observer with his back to the wind. The result agrees with the facts observed in the regions off the Southern Californian and Peruvian coasts very satisfactorily. The velocity of upwelling is computed at about 80 meters per month, a value consistent with that estimated by McEwen from observed hydrographic data. Next, it is shown that an offshore wind blowing perpendicular to the coast can also give rise to a similar circulation in the same vertical plane, but in this case with much weaker intensity. From these results it can be concluded that the most intense upwelling will occur when the wind makes an angle of 21°.5 with the coast line in offshore direction. In addition to these circulations in the vertical plane we have horizontal currents parallel to the coast. These will contribute to the formation of the coastal or longshore currents much debated recently. The horizontal components of the motion under consideration show a vertical variation very similar to the Ekman spiral at some distance from the coast.

(21) Joseph E. O'Hare (U. S. Navy Hydrographic Office, Washington 25, D. C.) A Shock-Wave Hypothesis on the Origin of the Oceanic Tide--The theory is advanced that the giant current systems which circulate the major ocean basins are the generators of the ocean tide. Accompanying each lunar transit, induced perturbations progress along the current axes from east to west and divert stream momentum into the surrounding water masses in a threefold manner: (1) Internal waves move out slowly along the thermoclines. (2) Submarine "jet currents" develop beneath congested points along the streams from the impact of turbulent energy upon the bottom. Escaping swistly in all directions, inertia-trajectoried jet currents, after long repetition, erode canyons and trenches into the bottom. (3) Long surface waves move out from the reacting current to produce the observed semi-diurnal tide along adjacent shores. Wave energy is focussed by the directive influence of standing current meanders so that certain coastal points are subjected to accentuated ranges. Tidal erosion, so patterned, has produced much of the existing coastal topography.

(22) Jack Oliver, A. P. Crary, and R. Cotell (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) Elastic Waves in Arctic Pack Ice--Elastic-wave propagation was studied in the Arctic ice pack, on the Beaufort Sea, the Arctic Ocean, and at near-shore locations. Ice thicknesses varied from 0.9 to 2.1 m and water depths from 1 1/2 to 3800 m. Values of the elastic constants were derived from the measured velocities of the longitudinal and shear waves and the density. Dispersive flexural waves and air-coupled flexural waves were examined in detail and were used to deduce ice thicknesses. A high-frequency arrival with a velocity of 1700 m/sec was detected, the theoretical justification of which is not yet determined.

SECTION OF VOLCANOLOGY

(1) R. M. Farquhar, R. D. Russell, and J. Tuzo Wilson (University of Toronto, Toronto, Canada) The Determination of the Ages of Lead Ores by Means of Their Isotopic Constitutions--Additional isotopic analyses have been made of lead from lead ores, some of which have been dated by established methods. Such abundances had already been shown to vary with the age of the ores but this variation was formerly held to be too irregular to provide accurate age determinations. However, two "age" values can be obtained for any ore from the Pb^{206} and Pb^{208} abundances. A theory is proposed which provides a method of determining the probable error for ages determined in this way. It is tentatively suggested that leads whose abundances fall within the prescribed limits of error can be approximately dated. Other leads are held to be anomalous. Their abundances can be explained by additions of radiogenic lead subsequent to the separation of the ores from their original ore magmas.

(2) R. D. Russell, R. M. Farquhar, and G. L. Cumming (University of Toronto, Toronto, Canada) The Isotopic Constitution of Sudbury Galenas--Isotopic analyses of lead from galenas obtained from two mines at Sudbury have previously been reported. These samples had higher Pb^{206} and Pb^{208} abundances than any other galenas yet examined. Additional samples have now been analyzed. Lead in galenas disseminated in the wall rock of the Frood Mine and in veinlets in deformed micropegmatite has the isotopic composition of lead separated about 1300 ± 100 million years ago and appears to be in no way "anomalous." However, galenas found in post-ore slips yield leads with anomalous Pb^{206} and Pb^{208} abundances. The anomalous abundances can be explained by simple radiogenic additions to the ordinary lead.

(3) David Gottfried (Geochemistry and Petrology Branch, U. S. Geological Survey, Washington, D. C.) The Age and Relationships of Radioactivity, Lead Content, and Physical Properties of Zircon Crystals from Ceylon--Mineralogic and radioactivity studies have been made on ten crystals of zircon from Ceylon. The data give unusually smooth curves to show relationships between optical properties, radioactivity, lead content, and specific gravity. Each sample consists of homogeneous material although a wide range of activity was measured from one sample to another. The omega index ranged from 1.922 to 1.811 and the lead content from 22 to 529 parts per million. Age calculations have been made and are based on the determination of activity by thick-source alpha counting and also on the spectrographic determination of lead. The zircon is believed to have been derived from a Precambrian pegmatite. Age determinations on the ten samples give consistent ages averaging about 567 million years.

(4) H. D. Holland, D. A. Schulz, and M. N. Bass (Princeton University, Princeton, N. J.) The Effect of Nuclear Radiation on the Structure of Zircon--The effects of nuclear radiation from the decay of members of the uranium, actino-uranium, and thorium series on the crystal structure of a suite of gem zircons from Ceylon have been studied. It has been found that the specific gravity of the Ceylon zircons is a smooth function of their alpha activity. The x-ray diffraction data indicate that there is a smooth increase of the unit cell dimensions during the early stages of the discomposition of the structure, and that the x-ray pattern of zircons of low specific gravity is characterized by broad diffraction maxima due to a glassy $ZrSiO_4$ phase. It is proposed that these observations can be understood in terms of the effects of atomic dislocations produced by alpha particles and recoil nuclei, and that the relations obtained between radiation damage and radiation dosage form an adequate basis for the determination of the age of zircons.

(5) J. A. Jacobs (University of Toronto, Toronto, Canada) Problems Connected with the Cooling of the Earth--The composition of the Earth's core is reviewed and a physical explanation is offered as to how the Earth's inner core may have become solid. The question of convection currents in the Earth's core is examined and it is estimated that convection can arise if the radioactive content of the inner core is only about two per cent of that in the crust. Finally it is shown that conduction alone will probably suffice to transfer the heat from the core through the surrounding mantle.

(7) L. O. Nicolaysen, L. T. Aldrich, and J. B. Doak (Carnegie Institution of Washington, Washington, D. C.) Age Measurements on African Micas by the Strontium-Rubidium Method--Certain spectrochemical and mass spectrometric procedures for determination of Rb and Sr in pegmatite micas have been investigated. Comparison of the two methods indicates that the mass spectrometric determinations, using stable isotope dilution, are more reproducible and less subject to systematic error. Fourteen new mass spectrometric age measurements have been made on ruby muscovites and lepidolites from Africa and Madagascar. The determinations of the Rb and Sr isotopes were made on 200-mgm samples of mica, using the solvent extraction, ion exchange, and solid sample emission techniques developed by Aldrich and Davis. The Rb content of these micas varied between 0.6 and 3.6 pct and the radiogenic Sr content varied between 13 and 240 micrograms Sr 87/gm. The Rb and Sr can each be determined with a precision of three per cent (plus or minus), and the absolute ages (which depend on the decay constant of Rb 87) are regarded as accurate to within ten per cent. The mean of recently published values of the decay constant is $1.13 \pm 0.04 \times 10^{-11}$ year $^{-1}$. The following ages have been measured

Location	Age m y	Location	Age m y
Popes Claim, S. Rhodesia	3740	Jakkalswater, Namaqualand	1100
Letaba, Transvaal	3850	Muika (1), Belgian Congo	1220
Hombolo, Tanganyika	3250	Muika (2), Belgian Congo	1210
M'bale (1), Uganda	2460	Karibib-Usakos II, S. W. Africa	600
M'bale (2), Uganda	2370	Sahatany, Madagascar	690
Lunya, Uganda	2340	Alto Ligonha, Mozambique	570
Kinderzitt, Namaqualand	1210	Dogon Daji, Nigeria	625

The ages of these pegmatites, and others recently given by Davis and Aldrich, supply new data for theories concerning the age and early history of the Earth. The measurements indicate that published syntheses of African Precambrian tectonics may need revision. The geologic implications are treated in detail in a separate publication.

(8) Claire C. Patterson, H. S. Brown, M. G. Inghram (University of Chicago and Argonne National Laboratories, Chicago, Ill.) E. S. Larsen, Jr. (U. S. Geological Survey, Washington, D. C.), and G. R. Tilton (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) The Distribution of Lead and Uranium in a Precambrian Granite--The isotopic compositions and concentrations of lead and uranium have been determined in some separated minerals and the composite rock of the red, gneissic granite from Monmouth Township, Haliburton Co., Ontario. Uranium was found to be concentrated primarily in the interstitial material and in the accessory minerals zircon, sphene, and apatite. A large fraction of the lead, like uranium, was found to exist interstitially; however, most of the intracrystalline non-radiogenic lead was found to reside in the feldspars and quartz. It is believed that the mean of the Pb^{207}/Pb^{206} and U^{238}/Pb^{206} ages for the zircon, 1050 ± 20 m y, is the most reliable indication of the time since gross crystallization of the rock. Consideration of the material balance for uranium and the isotopes of lead for this interval of time has led to the belief that, as a whole, the spatial distribution of these elements in the system studied here has not been static, and that the scale of relative transport of these elements must be considered. Either transport occurred on a micro scale such that the rock may be regarded as a closed system, or transport occurred on a macro scale such that the rock may be regarded as an open system. At present, the data are insufficient to warrant a decision; however, evidence is being accumulated which, it is hoped, will prove decisive.

(9) R. D. Russell, H. A. Shillibeer, and A. K. Mousuf (University of Toronto, Toronto, Canada) The Branching Ratio of Potassium-40--The radioactive isotope K^{40} decays both by beta emission to Ca^{40} and by K-electron capture to A^{40}. The rate of beta decay now seems well established at 29.6 ± 1.0 disintegrations per gram of potassium per second, but per 100 beta emissions from 2 to 15 K-electron captures have been reported. Fifteen potassium minerals have been analyzed for potassium and radiogenic argon. Five of these were collected from pegmatites dated by the isotopic analysis of lead from uranium minerals. These results indicate that there are 6.0 ± 1.0 K-electron captures per 100 beta emissions. Agreement between values obtained from microcline, perthite, and muscovite from the same pegmatites and between values from minerals differing in age between 400 and 1800 m y is strong evidence against any loss of argon from the minerals. It may be that further work will justify the use of this method for making approximate determinations of geological age.

(10) Hans E. Suess (U. S. Geological Survey, Washington, D. C.) A Note on the Isotopic Composition of Atmospheric Hydrogen--Liquid air companies find that their "crude neon" fraction always contains a noticeable amount of hydrogen. The figure of 0.5 part per million by volume for the concentration of free hydrogen in air is given by Paneth in 1939 and is the only one given in the literature. The question of the origin of this hydrogen can now be answered conclusively from its deuterium content. It is well known that any reaction generating hydrogen in equilibrium with water will yield hydrogen with a considerably lower deuterium content than that of the water from which it originates. Harteck and Suess, however, found from density measurements that a water sample which they had collected in 1948 by oxidizing atmospheric hydrogen was as heavy as or slightly heavier than laboratory water. Independently the Air Reduction Co. of New Jersey collected some samples in the same way at about the same time, and unpublished density measurements gave exactly the same result. This company has now kindly supplied the writer with several grams of atmospheric hydrogen in the form of water which was left over from these investigations. The deuterium content was recently redetermined with great precision by Urey's mass spectroscopic group in Chicago. The value found falls within the range of values for rain water. This confirms the earlier results and proves conclusively that the deuterium in free atmospheric hydrogen is not in thermodynamic equilibrium with water vapor. The only reaction by which hydrogen of this isotopic composition can be formed on the surface of the Earth is by the non-equilibrium photochemical decomposition of water vapor in the upper layers of the atmosphere.

The experimental proof for the existence of such a reaction is interesting in connection with the problem of hydrogen escape into space. Harteck and Jensen in 1948 estimated that the amount of hydrogen generated by photochemical decomposition of water vapor which had left the Earth during the past three billion years may perhaps correspond to a layer of 100 meters of water, or about 50 times the oxygen now present in the atmosphere. According to Kuiper in 1952 and to Bates and Nicolet in 1950 this figure is probably high by a factor of about ten. The lower figure seems still to be uncertain by a factor of about ten, and in view of the obvious geological implications, further empirical data bearing on the problem of hydrogen escape seem highly desirable. In this respect work now being carried out by W. F. Libby and coworkers on natural tritium seems highly promising. Independent of the discovery of tritium in surface water by Libby and Others, reported in 1951, Faltings and Harteck in 1950 found that the tritium in the sample of atmospheric hydrogen from the German Linde Co. was so high that it was easy to measure. A tritium determination of the sample obtained from the Air Reduction Co. carried out by Libby, has now confirmed this. According to Libby the tritium content of rain water varies for individual rainfalls within a range of a factor of ten and the two determinations on atmospheric hydrogen can hardly yield a very reliable average value. An accurate figure for the ratio of the tritium concentration in free hydrogen to that in rain water cannot therefore be stated but it seems that this ratio will probably be of the order of 1000. This ratio is connected in a simple manner with the rate constants for the photolysis of water vapor and for the oxidation of hydrogen in air, quantities entering into any estimate for the rate of escape of hydrogen from the Earth.

SECTION OF HYDROLOGY

(1) N. L. Stoltenberg (U. S. Soil Conservation Service, Purdue University, Lafayette, Ind.) Infiltration - Some Theoretical and Practical Aspects--Two equations of flow, the one developed by Hagen and Poiseuille in 1839-1840 and the other by Darcy in 1856, have been well substantiated. Full consideration of the fundamental differences and implications involved in these equations leads to a rational equation for flow through soils which is considered to be applicable to infiltration under certain conditions. Causes of the usual decrease in field infiltration rates during the course of a storm are discussed in relation to the flow equations and to other factors. Infiltration-rate curves from small (three acre) watersheds are presented which indicate a marked effect of differences in microtopography and specific limiting zones on field infiltration rates. Several methods are used to define the limiting zones. Seasonal infiltration-rate curves have been developed by a somewhat unique method and factors influencing the rate curves are discussed.

(2) V. S. Aronovici (U. S. Soil Conservation Service, Pomona, California) The Application of the Ring Infiltrometer to Diagnosis of Irrigation Problems in Southern California--The value of the one square foot metal ring infiltrometer as a diagnostic tool is being studied on a number of citrus groves in Southern California. Intake rates were measured through an entire irrigation run on one or a group of furrows. Intake rates are measured by means of ring infiltrometers placed in the furrows or adjacent to them. Soil cores are obtained of representative soil horizons and values of the coefficient of permeability obtained in the laboratory. Comparisons are drawn of the rings, soil cores, and furrow performance. It is found that the ring infiltrometer placed within the furrow during irrigation gives values somewhat below intake rates of the furrows. Infiltrometers placed outside the furrow without an outer buffer pond and driven into the ground approximately three inches produces results comparable or somewhat higher than the furrow. The exponential curves produced by plotting elapsed time with intake rates are in general similar. The tendency is for the intake rates of rings to fall off more rapidly than those of the irrigation furrow. There is no certain method of establishing what portions of the soil profile restricts infiltration when using the infiltrometer unless they are placed at several depths and the soil above removed. Soil cores are capable of detecting restricting layers, if present, but do not quantitatively reflect field performance of an irrigation furrow. Laboratory model studies of the ring infiltrometer have clearly illustrated the significance of placement, initial soil moisture and character of soil profile upon observed intake rates. Under conditions of low initial soil moisture, the primary force producing flow into the soil is a product of suction head. This head is dependent upon the capillary potential gradient at the wetting front and the ratio of the surface area of the wetting front to the surface area of the ring infiltrometer. This subject is discussed in detail in another paper now in manuscript entitled Model Tests of the Ring Infiltrometer under Low Initial Soil Moisture.

(3) M. J. Gilbert (Agronomy Department, North Carolina State College, Raleigh, N. C.) A Simple Field Method for Measuring Maximum Evapotranspiration--Soil-filled gasoline drums (55 gal) planted to various crops are used to measure maximum evapotranspiration at Waynesville, N. C. Installation involves no mechanical devices and maintenance is at a minimum. Water is added manually to prevent water supply to the plants from becoming a limiting factor. Tensiometers are used to indicate when water must be added. Tanks are placed in the center of areas of the same vegetation. Data for eight months under grass cover are presented and compared with values calculated from Thornthwaite's formula. Additional uses are indicated; comparison of maximum evapotranspiration under different crops and possibly measurement of actual evapotranspiration when no water is added.

(4) S. Irmay (Hydraulic Laboratory, Hebrew Institute of Technology, Haifa, Israel) An Electrical Analogy Method for Solving Problems of Two-Dimensional Flow in Non-Homogeneous Isotropic Media--Steady two-dimensional flow through saturated media at low Reynolds numbers, obeys Darcy law with a variable hydraulic conductivity (or permeability). The resulting differential

equation has the same form as that of the electrical current in an electrical analogy apparatus devised by Taylor for the study of compressible flow. The current is fed into a thin conducting sheet of electrolyte solution in a tank with wax bottom carved to a depth which is function of the permeability. This can be done in two ways, but the method has its limitations.

(5) N. J. Lusczynski (Ground Water Branch, U. S. Geological Survey, Mineola, N. Y.) Computation of Recharge to the Lloyd Sand Member of the Raritan Formation on Long Island, N. Y.--Recharge to a deep and extensive artesian aquifer on Long Island, N. Y., the Lloyd sand member of the Raritan formation, through the thick and relatively impermeable overlying clay member of the formation, is computed by the storage equation and substantiated by other data. The proportion of the recharge caused by the landward movement of the fresh water -- salt-water interface accompanying the lowering of piezometric levels is estimated for consideration in the calculations. The computed recharge, although approximate, yields a mean value of the coefficient of permeability for the Lloyd sand member consistent with figures determined from pumping tests, from the magnitude and time lag of water-level fluctuations in observation wells in response to ocean tides, and from piezometric-level profiles.

(6) Doak Cox (Experiment Sta., Hawaii Sugar Planters Assn., Honolulu 14, T. H.) and Walter Munk (Scripps Institution of Oceanography, La Jolla, Calif.) The Diffusion of Tides into the Volcanic Rock of Hawaii: A Method for Estimating Subsurface Permeability--Records of water level have been obtained from the irrigation wells on the island of Maui, T. H., at distances from 0.8 to 4.3 km from the coastline. Harmonic analyses of these records reveal diurnal and semidiurnal components. With increasing distance from shore, the amplitudes of these components diminish, and the time of high water is increasingly retarded. This diffusion-like behavior can be accounted for by a mathematical analysis of the problem. The agreement between theory and observations is only fair, but nevertheless the method may have some value for roughly estimating subsurface permeability.

(7) Sam Shulits (Michigan College of Mining and Technology, Houghton, Mich.) Graphical Analysis of Trend Profile of a Shortened Section of River--The effect on the profile of shortening a river section by one or more cut-offs can be analyzed graphically. The graphical method is based analytically on the well-known observation that river slope and particle size of bed material are closely related. The question of abrasion and selective transportation is considered briefly. The profile obtained is that towards which it trends as a result of the rectification but which it may never reach due to geologic and other unforeseen conditions. The time to reach the trend profile cannot yet be ascertained. The method illustrates the consequences of the interplay of cut-offs.

(9) Arthur N. Strahler (Dept. of Geology, Columbia University, New York 27, N. Y.) Revisions of Horton's Quantitative Factors in Erosional Terrain--Since Horton in 1945 introduced several useful quantitative factors to express form of erosional topography, application of these factors by the writer and his associates has necessitated certain revisions. Stream-order designation can be made more objective and useful by ruling that the junction of any two streams of the same order produces a stream of the next higher order. The bifurcation ratio becomes more truly representative of a stream system when computed as a weighted mean. Using these revised methods, Horton's law of stream numbers remains valid. On the other hand, Horton's law of stream lengths appears invalid in the light of new data which show that stream length and stream order are better related by a power function. Horton's drainage density factor has proved a most useful dimensional number for describing scale of drainage systems. Revised values range from as low as three miles of stream channel per square mile in resistant sandstones to as high as 800 in clay badlands.

(10) Troy L. Pewe and Lyman W. Taylor (U. S. Geological Survey, Washington, D. C.) Ablation Measurements on Black Rapids Glacier, Alaska--Black Rapids Glacier, in the central Alaska Range, is about 30 miles long and ranges in altitude from 2300 ft at its terminus to 8000 ft at the heads of tributary glaciers. After a rapid advance in 1937 the glacier had an ice front 300 ft high and a jagged but gently sloping ice surface. Since 1937 the glacier surface has wasted down, leaving prominent ice-cored moraine ridges 100 to 200 ft above a relatively smooth ice surface. Six 3/4-inch dowels of unpainted spruce inserted five feet into the ice at several places in the lower course of the glacier were read and reinserted sporadically during the summer of 1952. From these preliminary ablation measurements it is estimated that near the terminus at an altitude of 2450 ft the ice surface was lowered 18 to 20 feet during the five-month snow-free summer. At a 3100-foot altitude the ice surface was lowered an estimated eight to ten feet during a three-month snow-free period, and at 4200 feet it was lowered an estimated three to four feet during a two-month snow-free period.

(11) Joel E. Fisher (25 W. 43rd St., New York 36, N. Y.) Temperature Gradients Found in a (Cold) Glacier in the Alps--This is a report on temperatures observed at depths up to 50 m below the surface on a cold, high-altitude névé on Monte Rosa in the Alps. Altitude of site is 4100 m. Temperature at ten-meter depth was 16°F, dropping to 11°F at 50 m depth. No appreciable change in these temperatures was noted between June and August. The interior temperature is at the computed mean annual temperature of the atmosphere at this site. Indications are that it will continue to drop with further depth.

(12) Calvin J. Heusser (Osborn Botanical Laboratory, Yale University, New Haven, Conn. and American Geographical Society, New York, N. Y.), Robert L. Schuster (Snow, Ice and Permafrost Research Establishment, Wilmette, Illinois), and Arthur K. Gilkey (Department of Geology, Columbia University, N. Y.) Post - Wisconsin Glacier Maximum in the Juneau Ice Field, Alaska--Botanical and geomorphic evidence on ridges and nunataks bordering Taku Glacier, the main southerly drainage of the ice field, was studied with the purpose of ascertaining the change of level since the late-postglacial ice maximum. This maximum is known to have occurred between 2000 and 200 years ago. A trimline is evident at numerous localities and indicates the level to which the glacier cut the arctic-alpine heath. Below this level, there is a sharp change in the composition of the flora. In addition, differential rock weathering, fresh striae, and fracture cracks disclose the upper limit of overriding. A map has been drawn from these data, and a deleveling of as much as 500 ft is shown on some of the nunataks.

(13) C. H. M. van Bavel, E. E. Hood, and N. Underwood (Agronomy and Physics Departments, North Carolina State College, Raleigh, N. C.) Sample Size in the Neutron Scattering Method for Measuring Soil Moisture--A source of fast neutrons and a slow neutron detecting device in close proximity can serve to measure the moisture content of soil. The work was done with a ten-mc Ra-Be source and a BF_3-filled counter (2.5 × 30 cm). The volume of soil contributing 95 pct of the measured counting rate, referred to as the sample, has an ellipsoid shape. The horizontal diameter was less than 58 cm and the vertical diameter varied from 65 cm with very dry material (4.4 pct water by volume) to 45 cm with saturated material (38 pct water by volume). It has been shown possible, by partial shielding of the counting tube with Cd-foil to diminish the vertical diameter of the sample, at expense of counting rate. Counting rates varied between 16 and two cps.

(14) K. G. Reinhart and R. E. Taylor (U. S. Forest Service, Waterways Experiment Sta., Vicksburg, Miss.) Infiltration and Available Soil-Moisture Storage--This paper discusses (a) the effect of available storage on infiltration rates, (b) the relation of available storage to recovery of infiltration rates between storms or parts of the same storm, and (c) the use of a soil-moisture record determined by electrical resistance units to provide information about infiltration. The soils studied, ranging from silt-loams to clay, are of low permeability. As a result, infiltration rates obtained were quite low in spite of a good herbaceous cover. Recovery of infiltration rates in periods between runs was very slow because of this low permeability. Electrical resistance units were used to follow the downward movement of water during infiltration runs and to record the rate at which soil-moisture storage became available after runs.

(15) H. C. S. Thom (U. S. Weather Bureau, Washington, D. C.) The Generalized Log-Normal Distribution Applied to Stream Discharge--The statistical properties of the generalized logarithmic normal distribution are discussed and contrasted with the distribution commonly employed by hydrologists. The efficiency of estimation procedures is explained and fits are made to several examples of stream discharge series.

(16) William C. Ackermann (Tennessee Valley Authority, Knoxville, Tenn.) Effect of Fifteen Years of Forest-Cover Improvement upon Hydrologic Characteristics of White Hollow Watershed--A fifteen-year investigation of the hydrologic effects of forest-cover improvement has been carried out by the Tennessee Valley Authority. The 1715 acre White Hollow watershed in northeastern Tennessee had been in use for 150 years or more and most of it had been cleared and under cultivation at some time. Soils were generally severely eroded and not suited to agriculture. Planting and natural revegetation with protection from fire, grazing, and cutting have resulted in a greatly improved forest cover. Marked reductions in peak discharges have occurred. Discharge rates during the summer season have been reduced to only eight to 27 pct of those initially observed. The winter season discharge rates at the end of the period were 78 to 95 pct of the original rates. The greatest reductions in peak discharges took place during the first two or three years after cultivation stopped, smaller reductions continuing after that time. No appreciable change has occurred in the water yield from the watershed and there has been no shift between surface and ground-water runoff or in the seasonal runoff pattern.

(17) Louis H. Bean (U. S. Dept. of Agriculture, Washington, D. C.) Long-Range Forecasts of Floods in the Columbia and Missouri Rivers--This paper has a two-fold purpose: It first brings to date the study presented to this Section a year ago on a short-cut graphic method of forecasting the annual variations in the maximum flow of the Columbia River at the Dalles by means of expected patterns of fluctuations based on characteristics of the record. In the study it was shown, among other findings, that the record floods of the Columbia River in 1894 and in 1948 could have been anticipated at least a year in advance, and that the 1950, 1951 and 1952 above normal maxima were actually predicted more than a year in advance with a high degree of accuracy. The second purpose is to present a similar study of the total annual Missouri River runoff at Sioux City, Iowa, and to show that the non-random character of this record, like the one for the Columbia River, made possible highly accurate predictions for the 1950-51 and 1951-52 water years. At least two years in advance, the analyses pointed to the prospect of the flood trouble at Sioux City in the 1951-52 season.

(18) J. L. H. Paulhus (Cooperative Studies Section, U. S. Weather Bureau, Washington, D. C.) A Frequency Study of Ten- to 120-Minute Rainfall Intensities--The objective of a rainfall-intensity frequency study now in progress is the determination of the ten- to 120-minute rainfall intensities expected to be equaled or exceeded once in two, five, and ten years in western United States. The project is sponsored by the Office of the Chief of Engineers, Department of the Army, as one of several investigations leading to the development of drainage design criteria for military construction. Time and cost limitations necessitate use of basic data already evaluated. These data consist mostly of clock-hour precipitation amounts for records averaging slightly less than ten years at about 500 stations in the project area. Supplementing these data are tabulations of annual maximum amounts for durations from five to 120 minutes at about 25 stations with records averaging about 40 years. The data from these 25 stations are used to adjust the basic clock-hour data to attain the project's objective.

(19) Robert F. Black (U. S. Geological Survey, Washington, D. C.) Precipitation at Barrow, Alaska, Greater than Recorded--The records of the U. S. Weather Bureau station at Barrow, Alaska, show a mean annual precipitation of 4.23 inches, of which about half is snow. For the period between October 1, 1949, and June 20, 1950, the station reported 20.1 inches of snow with a water equivalent of 2.22 inches but an average depth of snow on the ground during May 6-12, 1950, of 23 inches. Of the 263 days only 43 were without precipitation; only 2.2 inches of snow fell on days with wind less than 15 mph. The writer's study showed that snow on the ground averaged 0.4 density and had a water equivalent of 9.2 inches -- four times that recorded. In addition considerable snow was removed from the ground by wind prior to measurement and was lost at sea. Wind velocities are higher in summer than in winter and precipitation occurs almost daily as drizzle that the gage does not catch efficiently. Average annual efficiency of the gage may be only 25 pct, and mean annual precipitation at Barrow may be more than 16 inches.

(20) L. L. Weiss and W. T. Wilson (Hydrologic Services Division, U. S. Weather Bureau, Washington, D. C.) Evaluation of Significance of Slope Changes in Double-Mass Curves--Interpretation of double-mass curves frequently involves rejection or acceptance of indicated changes in slope. Often, the decision must be based on inadequate station records. In any case, it is important that the analyst should know the probability of getting an abrupt slope change purely by chance. The significance of any slope change can be evaluated by a statistical treatment making use of range instead of standard deviations. The application is simplified by a special protractor and simple nomograph. The double-mass method is commonly used in the interpretation of precipitation records.

(21) Joseph I. Burns (California Division of Water Resources, Sacramento, Calif.) Small-Scale Topographic Effects on Precipitation Distribution in San Dimas Experimental Forest--The topographic parameters, elevation, slope, rise, aspect, and zone of influence, are correlated with annual precipitation for the San Dimas Experimental Forest in a multiple-graphical correlation. From this relation it is possible to make an estimate of precipitation at any point in the Forest area with a greater degree of accuracy than when elevation alone is used. The correlation was developed from 11 years of record for 96 gages and a completely independent check was obtained from data for the same period of record for 45 gages which were not used in the graphical development. This study confirms Spreen's investigation for western Colorado and shows the same general technique of graphical correlation of precipitation with topographic parameters is applicable through a wide range of topographical and meteorological conditions. Two test cases are not necessarily sufficient to test the universality of the method, however, it can be assumed that the method can be used to adjust estimates of the mean annual precipitation in other areas.

(22) John T. Riedel (Hydrologic Services Division, U. S. Weather Bureau, Washington, D. C.) Topographically Adjusted Mean Annual Isohyetal Map for New England - New York Area--As a part of a Federal-State survey of the water, land, and related resources of the New England States and New York, the U. S. Weather Bureau prepared mean annual isohyetal maps adjusted for topographic parameters. The mean precipitation is based on the average for the 20-year period 1930-1949. The area was divided into sub-regions, and graphical relations between precipitation and various topographic parameters were developed for each sub-region. A particular parameter did not necessarily give good results for each sub-region. Altitude in all cases was the most important parameter. The correlation between observed and computed precipitation varied from basin to basin, but averaged about 0.90. A brief summary and evaluation of all parameters used are given, and the relations for each area shown. Possible errors in the basic data and the smoothed construction of the final map are also discussed.

(23) Lillian H. Madow (Illinois State Water Survey Div., Urbana, Ill.) Estimation of Mean Rainfall with Various Gage Densities in a Dense Raingage Network--The variance of mean precipitation of subsamples of gages about the mean of all gages in a 95-square mile area in central Illinois is calculated for the period May through September for three years. For 1950, 36 gages are studied on a storm-day basis, and for 1951 and 1952, 24 gages are studied on a storm basis. The random start systematic, centered systematic, and unrestricted random sampling variances are calculated and compared. A curve of the form $\sigma = AP^{B}n^{C}$, where σ is the true standard deviation of the mean of a sample is size n, P is the mean of all the gages in the area, and A, B, and C are constants, is fitted to the random start systematic sampling standard deviation. For 1950, the equation becomes $\hat{s} = 0.387P^{0.562}n^{-0.867}$, where $\hat{s}$ is the estimate of σ. Confidence bands for P, based on this equation, are calculated. For each of the three years, 1950, 1951, 1952, over 90 percent of the population average rainfalls (the average of all gages in the network) fall within the confidence limits computed using the 1950 formula given above.

(24) Paul E. Damon and P. F. Kuroda (University of Arkansas, Fayetteville, Ark.) On the Natural Radioactivity of Rainfall--Measurements by the authors of the natural radioactivity of rain water are reported. The radioactivity varied from six to 60 millimicrocuries per liter of rain water and was due primarily to RaB + C. The activities due to ThB and RaD were less than 0.1 millimicrocurie per liter each. RaA is present in rain water at the time it reaches the Earth's surface. A mechanism for the accumulation of decay products in rain water is discussed. A semi-empirical equation is derived, indicating that the total activity (per unit area and time) increases exponentially toward the limiting value determined by the supply of RaA from Rn. An average atmospheric Rn concentration within the cloud system of approximately 0.2×10^{-13} curie per liter is sufficient to supply the rain water with the observed radioactivity. The natural radioactivity of the atmosphere can be used as a tracer to study meteorological phenomena.

(25) John Sherrod, Jr. (Technical Information Division, Library of Congress, Washington, D. C.) A Bibliography on Snow, Ice, and Permafrost--The Technical Information Division, Library of Congress, under an agreement with the Snow, Ice, and Permafrost Research Establishment (SIPRE), Corps of Engineers, U. S. Army, is preparing a bibliography with abstracts on the basic properties and applications of snow, ice, and frozen ground. Nearly 5000 abstracts have been made from works published in any of 16 languages. Methods used in selecting material and publication procedures of the project are reviewed.

(26) Stanley A. Schumm (Dept. of Geology, Columbia University, New York, N. Y.) Erosion Measured on Badland Slopes--Typical badland topography has developed in a terrace of sand-clay fill at Perth Amboy, New Jersey. Depth of sheet runoff erosion on the badland slopes was measured from the progressive exposure of stakes. Slopes are six to 14 ft long; are straight from crest to base except for convex divides and minor irregularities. Mean depth of erosion during ten weeks observation was 0.9 inches. Statistical tests indicate no significant departure from uniform erosion depth. In addition, slope angles measured between successive stakes at the beginning and end of the study, and a sampling of maximum slope angles measured in 1948 and 1952 showed no significant changes of angle. The results suggest that parallel slope retreat may be occurring here.

(28) L. M. Glymph (Soil Conservation Service, Lincoln, Nebr.) Water Erosion Problems and Control on Non-Irrigated Agricultural Lands--The principal types of water erosion on non-irrigated agricultural lands are described and their extent estimated for groups of states. Selected summary data on rates of soil loss from 0.01-acre plots in grasses, continuous row crops, and adopted crop rotations are given from nine experiment stations in important farming areas. Factors influencing rates of erosion are enumerated and discussed briefly. The objective of erosion control on agricultural lands is specified and some of the methods and principles of erosion control are listed.

(29) Joel E. Fletcher, Karl Harris, H. B. Peterson, and Verlin Chandler (U. S. Soil Conservation Service, Tucson, Ariz.) Piping--"Piping," "Tunnelling," or "Rodentless Rodent Erosion" is an insidious type of erosion wherein the subsoil erodes away allowing the surface soil to cave-in leaving a series of pits joined by tunnels or, in the final stages, merely a chain of gullies with vertically incised walls. This type erosion is widespread, though seldom recognized over the world. Its worst ravages, however, are in narrow alluvial valleys. Here it appears to be the most serious type of erosion present. It is shown that piping cannot occur unless all of the five following conditions are present: (1) The surface infiltration rate must exceed the permeability of some layer below. (2) There must be an erodible layer immediately above the retarding layer. (3) The water above the retarding layer must be under a hydraulic gradient. (4) There must be a source of water. (5) There must be an outlet for the lateral flow. A detailed study of five areas of Arizona confirmed the necessity for the five above-stated conditions to be present.

(30) Martin R. Huberty (University of California, Los Angeles, Calif.) Some Observations on Soil Erosion in the Middle and Eastern Mediterranean Area--The question is raised whether soil erosion on the karstic formations, so common in parts of the Mediterranean area, has ever been a serious problem. Some of the soil and water conservation practices of the Romans are described as well as the present practices and organizations in a number of countries in the middle and eastern Mediterranean region.

(31) J. D. Sinclair (U. S. Forest Service, Glendora, Calif.) Erosion in the San Gabriel Mountains of California--Natural conditions of climate, topography, geology, and soil in the San Gabriel Mountains are conducive to high rates of erosion. When the vegetation on steep slopes is removed as by fire, or if the land surface is disturbed, erosion may be greatly accelerated through increased surface runoff. Loss of life and extensive damages have been caused downstream by debris-laden floods from the mountains. Removal of soil by erosion also affects adversely conditions on the mountain watersheds. Eroded material carried by flood flows greatly increases their destructive capacity and complicates the problems of flood regulation. Solution of these problems has been sought mainly through protection of the vegetation cover on the mountains from fire and by construction of extensive engineering works, the latter mostly downstream. Studies are being made by the U. S. Forest Service concerning sources, processes, and rates of erosion on the mountain slopes and of means to increase the stability of soils by improving the vegetation on areas where erosion is most severe.

(33) Henry W. Anderson (California Forest and Range Experiment Sta., Berkeley, Calif.) Suspended Sediment as Related to Watershed Streamflow, Soils, Topography, and Land Use--Suspended-sediment sampling results were used to obtain average annual suspended-sediment production from 29 watersheds of western Oregon by relation of sediment to discharge and by use of discharge frequencies. The values of average suspended sediment thus obtained were related by regression analysis to average watershed values of two streamflow variables, two topographic variables, one channel bank variable, four land use variables, and two soil variables. The soil variables were obtained by taking samples of the surface soil at standardized locations in the major geologic types, analysing the samples for particle size and dispersion characteristics, and expressing these characteristics as watershed averages. The other variables were obtained from published maps and other secondary sources. It was estimated that 54 pct of the present sediment production of the Willamette River came from eroding channel banks. The regression results were used to construct a map of the sediment potential of the land areas of western Oregon for average land use conditions; regression coefficients indicated how the actual production of sediment would differ from the potential with deviations of land use from average.

SECTION OF TECTONOPHYSICS

(1) Joel E. Fisher (25 W. 43rd St., New York 36, N. Y.) Arguments for a Solid Central Core of the Earth at 0° K--Excess of solar radiation received less radiation lost by the Earth into space is 4.5×10^{23} calories per annum. This demands some kind of heat sink within the Earth itself. One such heat sink could be found by accepting universal gravitation as having once been more powerful than today, consequently existing core densities were produced by compression under earlier more powerful gravitation. Then, as gravitation diminished, expansion of core would have involved cooling, eventually reaching absolute 0° K. As a check, there is developed an equation for the velocity of long-period compression waves, through a solid, at 0° K, which indicates a velocity in such a cold core well under the classical $V = \sqrt{y/\rho}$ thus accounting for observed velocities of P Waves, etc. Expansion of such a cold core would absorb that otherwise unaccounted excess receipt of solar heat by the Earth over loss of heat by radiation as well as radioactive heat produced in the mantle.

(2) David Griggs and Francis J. Turner (Institute of Geophysics, University of California, Los Angeles, Calif.) Deformation of Rocks at Moderate Temperatures and Pressures--Results of recent experiments at 300° C, 5000 atmospheres confining pressure, and at 400° C, 3000 atmospheres confining pressure will be presented. Deductions as to mechanisms of deformation based on physical properties and microscopic analysis will be briefly discussed. In particular, evidence for recrystallization flow of marble will be given. Evidence of plastic flow in dolomite, dunite, and granite will be presented.

(3(William W. Rubey (U. S. Geological Survey, Washington, D. C.) Tectonic Consequences of Crustal Growth by Selective Fusion--A review of the geologic history of sea-water indicates that CO_2, H_2O, and other volatiles have been rising continuously to the Earth's surface and that this calls for the continued generation of hydrous granitic magmas through geologic time. The suggested mechanism of crustal growth by selective fusion of sub-crustal rocks logically implies certain tectonic consequences that can be compared with observational data. The lowest melting constituents of peridotitic rocks beneath active mountains and geosynclines are probably at melting temperature below about 100 km depth. Birch's analysis of seismic velocities may be interpreted to mean that the Earth's mantle below 900 km is still undifferentiated, but from there upwards consists partly of unmelted residuum left after the low-melting constituents have been squeezed out to form the crust. Resultant over-thickening of the mountain roots in active areas would eventually cause crustal spreading and buckling up of new mountains above the sites of earlier geosynclines.

(4) J. Tuzo Wilson (University of Toronto, Toronto, Canada) On Grabens, Rifts, Major Wrench Faults, and Straight Chains of Islands--Many of the above features occur within or joining primary mountain arcs like the great faults of California, British Columbia, Philippines, Sumatra, New Guinea, New Zealand, west Newfoundland-Nova Scotia, Venezuela, and the Caribbean Sea. Others occur along boundaries between corresponding primary and secondary mountains like Rocky Mountain Trench, Great Slave Lake, Bathurst Inlet, Cusco, and north Turkey faults. Still others spring at 45° to 60° from the continental side of mountain systems, like the Rhine, Ottawa and Saguenay grabens and the fault uplifts of interior United States and Scotland. Straight island chains occur in the central Pacific. The African rifts and Darling scarp are special cases. All have in common large size, straight traces, or segments, and occasional to frequent volcanism. All properties follow from E. M. Anderson's explanation of wrench (transcurrent) faults. Very large horizontal displacements should be accompanied by large and irregular vertical movements which serve to explain grabens.

(5) Matt Walton (Dept. of Geology, Yale University, New Haven, Conn.) Differential Metamorphic Mobilization and the Adirondack Eruptive Sequence--The sequence in time and place of major rock units in the Adirondacks is reinterpreted as a secondary metamorphic modification of an originally different primary sequence. The Grenville series, the anorthosite suite, the "basic gabbros," and the syenite-granite suite existed prior to an episode of profound penetrative deformation and metamorphism. The present relations of these units largely result from differences in mechanical mobility and physical-chemical stability during metamorphism. The anorthosite and syenite suites were genetically related, but paratectonic recrystallization and palingenesis of a granitic magma fraction in the syenite made the syenite suite more mobile and it assumed seemingly independent late relations to anorthosite. Both were emplaced at present positions in the Grenville during this process. Possibly the Grenville originally overlay a primary syenite-anorthosite complex. Other primary relationships underwent analagous modifications. The concept of differential metamorphic mobilization may be fundamental in unraveling sequences in regions of profound deformation.

(6) W. S. Burbank (U. S. Geological Survey, Washington, D. C.) Thermodynamics of Metasomatism, Energy Conversion, and Flow of Heat in the Earth's Crust--A general expression is derived for the slope of the vapor-pressure curve in an ideal volume-for-volume exchange reaction in a rigid semi-permeable environment. In the limiting quasi-reversible case the decrease of free energy exceeds the heat of reaction. Irreversibility leads to generation and flow of heat to the environment, to partial fusion and loss of rigidity, and in turn to partial conversion of the Earth's gravitational energy to chemical energy and other useful work. The processes are activated and catalized by condensible volatiles squeezed from deeper layers of the crust and mantle, as indicated by Rubey. Theoretically such systems would yield multi-layered structures for the deeper crust and mantle, resulting from layer-by-layer saturation and partial fusion. The converted available energy may become ponded to such a degree that magmatic and volcanic phenomena are produced on a large scale. The bearing of such processes on localization of igneous activity in the continents, on configuration of island arcs, and on Jeffry's model of a shrinking Earth is considered briefly.

(7) Brian Mason (Department of Geology, Indiana University, Bloomington, Indiana) Polymorphism and Orogeny--Two distinct causes are currently invoked to explain orogeny: thermal contraction of the Earth, and sub-crustal convection currents. The purpose of this paper is to examine a third possibility: contraction as a result of a polymorphic change of the material within the Earth. In 1936 Bernal suggested a polymorphic change of $(Mg, Fe)_2SiO_4$ to explain the 20° discontinuity within the mantle; this suggestion is extended by proposing that the relative amounts of the polymorphic forms have varied during geological time. An increase in the amount of the denser polymorph would lead to a contraction of the Earth as a whole, resulting in crustal shortening and orogeny. Calculations show that the observed crustal shortening as a result of orogeny during geological time can be explained on this hypothesis.

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Program for 1953
American Geophysical Union,
1530 P Street, Northwest,
Washington 5, D. C.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 34 June 1953 Number 3

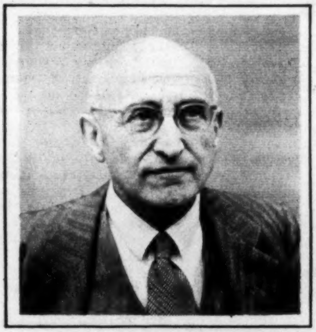
FIFTEENTH AWARD OF THE WILLIAM BOWIE MEDAL

CITATION

Prepared and presented by Perry Byerly

Mr. President, Members and Friends of the American Geophysical Union: I am most happy today to be able to present my old friend, Beno Gutenberg, as recipient of the Bowie Medal. No one whom I know has shown such devotion to his scientific work and yet remained essentially a "home" man, a devoted and much loved son, husband, and father.

His labors in seismology have been prodigious and unceasing, and his accomplishments so great that it is rare that anyone writes a paper in seismology without referring to him.



Beno Gutenberg
Recipient, Fifteenth Award,
William Bowie Medal - May 4, 1953

I first met Professor Gutenberg in the spring of 1929, when I spent a week in Darmstadt with him. I well remember seeking out his house on Mill Street. My German was and is poor, and when I asked a passer-by for Mühlstrasse he could not understand. Finally I said "B. Gutenberg" and his face lit up, "Oh, My-y-ylstrasse."

The Gutenbergs invited me to dinner that evening and I did enjoy the home cooking and the German menu. Professor Gutenberg's mother spoke English so well that I asked her when she had been abroad to learn it. She then told me that she learned English at school in Darmstadt! I still remember her looking fondly at her son and saying, "Beno is so good." I was much impressed with the charm of their family life. When I returned to the hotel, Arthur, then about seven years old, guided me. I tried to speak German to him but it was a failure. When he returned home, he said to his father, "The man is dumb."

I remember the large study with dark mahogany furniture, huge desk, and great porcelain stove. It was here that the Handbuch der Geophysik was edited and much of it written, here the Lehrbuch der Geophysik was written, the Grundlage der Erdbebenkunde, and many chapters of Sieberg's Erdbebenkunde; besides these, dozens of papers for the journals. In addition to all this writing and his lectures at the University of Frankfort, Professor Gutenberg directed the family business inherited from his father. It was unbelievable the amount of work he could turn out.

I had just seen in Cambridge Wadati's first paper on deep-focus earthquakes and was able to call Professor Gutenberg's attention to it. He read it and we agreed that Wadati had proved his case.

Beno took me up to the Feldberg (Taunus) Observatory on Saturday. The trip involved a short railroad ride and then a pleasant climb up the small mountain through the forest, idyllic to an American who had read of German forests. At the mountain top was an inn where we drank beer. Then we went over to the Observatory and saw the Galitzin seismographs. Dr. Gutenberg had shortened the period of one, looking for any indications of dispersion in P waves. Another day I went with him to Frankfort to the University, meeting Professor Linke.

It was in the fall of 1929 that the Carnegie Institution of Washington called a conference in seismology in Pasadena to make recommendations for the future of the Seismological Laboratory. There I met Beno for the second time. The outcome of the conference was that Gutenberg became Professor of Geophysics at the California Institute of Technology and later Director of the Seismological Laboratory. The rapid development of that laboratory since he came in 1931 is known to you all.

It is with great pleasure, Mr. President, that I present to you Beno Gutenberg.

Presentation by President Walter H. Bucher

Dr. Gutenberg, Members, and Friends: The Limes Germanus, the frontier wall of the old Roman Empire, ran along the crest of the Taunus Mountains not far from the Observatory, where you did your early work in seismology. Like the laboratory of your earlier days, you yourself have always stood on the frontier, the outer frontier not only of seismology, but of the whole empire of geophysical knowledge. You have been a general who not only knew how to conquer and marshal facts, but also how to win the cooperation of fellow officers in joint enterprises such as the Handbuch der Geophysik, in volumes of its successor in the National Research Council's Physics of the Earth Series, and in meetings like those of the Committee on the Physics of the Interior of the Earth which you organized in connection with the General Assembly of the Internationsl Union of Geodesy and Geophysics in 1951. Like a true leader, you have led the way with the products of your own ceaseless creative scholarship. In seismology, especially, your work has contributed to every line of thought. One of your books, written jointly with Professor Richter, the Seismicity of the Earth, is such a source of information and of inspiration that I may be forgiven for suggesting that it might well be called our own Gutenberg's Bible.

It is a great pleasure and honor for me to hand to you, Dr. Beno Gutenberg, in the name of the American Geophysical Union, this token of our admiration and gratitude, the Bowie Medal.

Response and Acceptance by Beno Gutenberg

Mr. President: It is a great honor to receive the Bowie Medal and to join the group of distinguished geophysicists who have received it previously.

Dr. Byerly in his citation has mentioned his visit to Europe in 1929 and the status of geophysics at that time. I should like to go back still further and to give a short review of geophysics and training in geophysics at the time when I was a student.

Originally I had intended to study mathematics and physics, although during school years I already had an interest in problems of weather forecasting and climatology. Thus, when as a sophomore, as it would be called here, in Göttingen in 1908 I found that a course on instrumental observations of geophysical phenomena was offered at the Geophysical Institute under Professor Wiechert, I took this course together with three other students. We were introduced there into observational methods of meteorology, into the handling of seismographs, the reading of the records, and the determination of exact time by astronomical means. In addition, I took three lecture courses by Professor Wiechert during that sophomore year, one on terrestrial magnetism, one on tides, and one on geodesy. During my third student year, I followed this up with a course on earthquakes, a geophysical seminar, and advanced laboratory work in seismology, all under Professor Wiechert, who then told me that I had learned practically all that was known in seismology, and was prepared to continue with research for a Ph.D. thesis. Since this looked very promising, I accepted it. Professor Wiechert suggested two general problems, which are just as good thesis problems today as they were then, one on microseisms and the other on seismic surface waves. I took the first and during the following year not only worked out my thesis but upon request by Professor Wiechert I reviewed an unfinished paper of the late Dr. Zoeppritz on the use of amplitudes of seismic waves through the Earth. I realized that the use of amplitudes to study the structure of the Earth looked very encouraging and, jointly with Dr. Ludwig Geiger, expanded the theory and use of the "Zoeppritz method." The resulting two papers were submitted to the Göttingen Academy by Professor Wiechert. During this and the following year I also had courses on general geophysics, meteorology, and atmospheric electricity by Professor Wiechert. Most of geophysics, especially seismology, had entered the so-called classic period; however, weather forecasting was still mainly an art, and meteorology was a more or less statistical science, although it was already well known at that time that there were sectors of different air masses around a low-pressure area and that the decrease of temperature with elevation stopped at the stratosphere. In a laboratory course on terrestrial magnetism in 1911, Dr. Angenheister showed us the use of the fundamental instruments, and Professor Waldemar Voigt, in connection with a general course on optics, gave weekly lectures on the rainbow. Unfortunately, the field of meteorological optics has been greatly neglected in recent years.

After my fourth academic year, shortly before my 22nd birthday, I passed my Ph.D. examination and a few months later I delivered the required 200 reprints of my thesis and received the degree. This may seem rather young but actually the majority of my friends, not only in geophysics, received their Ph.D. degree during the fifth academic year; a minimum of four years was required. This was made possible by the fact that before entering the university one had to show familiarity with at least two languages which depended upon the chosen field of study. Also in the Realgymnasium in Darmstadt, as in many other similar schools (which we would group together as high schools here), the fundamental principles of calculus were already being taught. This was made possible by a much heavier schedule in the "grammar school" than is customary here. It was certainly no fun for a nine-year old to have seven hours of Latin a week in the fourth grade and for many eleven- and twelve-year olds no pleasure to spend several hours a week on algebra and geometry, but it permitted the introduction of fundamental courses in physics and chemistry at "high school" and better preparation for university careers. The fact that a relatively large percentage of boys (relatively few girls went to a university) had to repeat grades or even dropped out and consequently were unable to enter a university was not considered serious.

Most students had no difficulty in taking advanced calculus and advanced physics in their "freshman year" and got an early basis for advanced study in all fields of natural science. For example, during my second year at the university I took courses on principles of mathematics by Hilbert, mechanics by Klein, and algebra by Minkowski; during my third year I took theory of numbers by Hilbert, infinite series by Landau, potential theory by Wiechert, non-Euclidian geometry by Klein, elasticity by Born, and a year later theory of functions by Weyl, as well as mathematical exercises for advanced students by Landau. However, after receiving my degree, I felt not yet ready for a full-time assistantship but took one more year of advanced courses and research during which I worked out and finished my paper on the Earth's core.

After serving one year in the army I entered the International Seismological Central Station in Strasbourg as assistant. There I realized the necessity of scientific cooperation among geophysicists in all countries. I had many discussions on this question with Dr. Bowie when I came to this country, and was glad to find that he, too, believed that cooperative research in geophysics is one of the requirements for progress in geophysics.

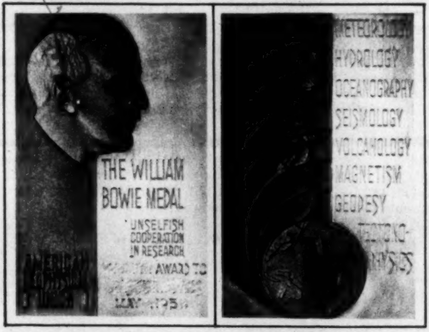
Mr. President, I accept the Bowie medal with deep gratitude.

Transactions, American Geophysical Union Volume 34, Number 3 June 1953

THE WILLIAM BOWIE MEDAL

The William Bowie Medal was established by deed of gift from Trinity College, Hartford, Connecticut in 1939 in honor of the distinguished and beloved geodesist and geophysicist whose name and likeness it bears. It is awarded annually in the name of the American Geophysical Union for distinguished attainment and outstanding contribution to the advancement of cooperative research in fundamental geophysics. The William Bowie Medalists, with the dates of their awards, are:

William Bowie (deceased)	1939
Arthur Louis Day	1940
John Adam Fleming	1941
Nicholas Hunter Heck	1942
Oscar Edward Meinzer (deceased)	1943
Henry Bryant Bigelow	1944
Jakob Aall Bonnevie Bjerknes	1945
Reginald Alsworth Daly	1946
Felix Andries Vening Meinesz	1947
James Bernard Macelwane	1948
Walter Davis Lambert	1949
Leason Heberling Adams	1950
Harald Ulrik Sverdrup	1951
Harold Jeffreys	1952
Beno Gutenberg	1953


THE WILLIAM
BOWIE MEDAL
UNSELFISH
COOPERATION
IN RESEARCH
AWARD TO
AMERICAN
METEOROLOGY
HYDROLOGY
OCEANOGRAPHY
SEISMOLOGY
VOLCANOLOGY
MAGNETISM
GEODESY
TECTONO-
PHYSICS

William Bowie Medal (actual size is 2" × 3 1/4")

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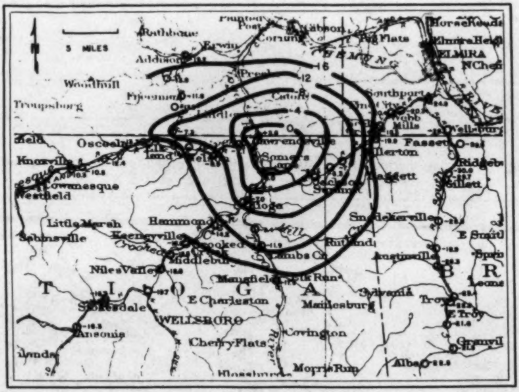
GRAVITY INVESTIGATION IN NORTH-CENTRAL PENNSYLVANIA

B. F. Howell, Jr., and Keeva Vozoff

Abstract--A gravity survey of about 900 sq mi in Tioga County, Pennsylvania, is described. Within this area a positive anomaly of 22 mgals is observed. It is shown that the greater part of this could be accounted for by the presence of a buried intrusion of diabase or peridotite.

In the summer of 1948, BACON [1950] ran a group of gravimeter surveys in central Pennsylvania, one of which extended from Amity Hall to Tioga, Tioga County. Plotted in profile, this traverse showed an increase of 14 mgals in the eight miles between Mansfield and Tioga. When compared with the rest of the survey, this appeared to be an outstanding anomaly. The question of how far this rapid increase continued northward and the possibility that its size and shape might divulge information on the basement structure of the area made the anomaly seem worthy of further investigation.

An area of about 900 sq mi centering on Lawrenceville, six miles north of Tioga, was surveyed. The observed values of gravity, corrected for instrumental drift, latitude, elevation, Bouguer effect, and topography, are shown on Figure 1.


5 MILES
16
12
8
4
0
Rathbone
Addison
Erwin
Corning
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Big Flats
Elmira Heights
ELMIRA
N Chemung
Woodhull
Troupsburg
Presho
Caton
Lindley
Southport
Webb Mills
Wellsburg
Osceola
Elkland
Nelson
Lawrenceville
Somers Lane
Knoxville
Cowanesque
Westfield
Fassett
Millerton
Ridgebury
Daggett
Gillett
Tioga
Hammond
Little Marsh
Sabinsville
Keeneyville
Crooked Creek
Middlebury
Mitchell Creek
Lambs Cr
Rutland
Snedekerville
E Smithfield
Austinville
Niles Valley
Mansfield
Elk Run
Sylvania
Troy
E Troy
T I O G A
B R
E Charleston
Mainesburg
Stokesdale
WELLSBORO
Ansonia
Covington
Cherry Flats
River
Morris Run
Blossburg
Alba
Granville

Fig. 1--Map showing observed gravity values

This area lies on the northwest limb of the Appalachian Synclinorium. Superimposed upon this major structure is a series of minor folds whose axes trend N 70° E, parallel to the long axis of the main trough. Drilling done in connection with gas deposits has shown the structure to be more complex than the gentle folds at the surface would indicate [CATHCART, 1934].

The rocks outcropping in the area range from upper Devonian (Portage) to Pennsylvanian (Allegheny) age, neglecting glacial and recent fluvial deposits [CATHCART and MYERS, 1934; TORREY and Others, 1932]. The greatest part of the area is covered by rocks of the Chemung formation consisting of shale, sandy shale, and sandstone. However, along the axis of the Blossburg syncline the Allegheny is found at the tops of the hills; and in the anticlines in Farmington Township erosion has penetrated through the Chemung into the Portage shale. Gas wells drilled to as much as 7000 ft have penetrated only to the Medina formation (Silurian). Geologic evidence as to the depth of the crystalline basement is lacking. There are no known outcrops of either basement or intrusive rocks within 50 mi.

Few data are available on the densities of the formations known to underly this part of Pennsylvania. NETTLETON [1940] gives a density of 2.67 gm/cc as an average of all crustal rocks. BACON [1950] assumed the density at the surface to be 2.64 gm/cc in making gravity corrections. A value of 2.65 was used here. As this is close to the density of most common basement rocks, variations in the basement surface elevation probably are not the chief cause of the observed anomaly.

Since the shape of the main gravity anomaly shows no relationship to the known Appalachian structural trends, it is possible that it results from a post-Paleozoic structure. Furthermore, it is difficult to see how so large an anomaly would result from other than a large density contrast which would almost rule out any purely sedimentary structure. The most marked time of igneous activity in northeastern North America since the Paleozoic was the Triassic, at which time large amounts of diabase were intruded at a number of places. The average density of diabase is 2.97 gm/cc [BIRCH 1942, p. 14] which would give a density contrast of 0.32 gm/cc. An intrusion of this sort would be capable of causing the observed anomaly.

Another possible explanation would be a peridotite body such as reported by HONESS and GRAEBER [1926] in Indiana County, Pennsylvania. The Tioga area lies on or close to the arc reported by these writers to extend from near Syracuse, New York, to Harrisburg, Illinois, along which peridotite dikes are common. The date of these intrusions is unknown, except that they cut rocks of Pennsylvanian age. The density of peridotite is about 3.2 gm/cc [BIRCH, 1942, p. 14] which would provide a density contrast of 0.55 gm/cc.

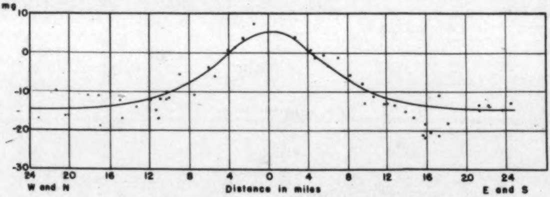
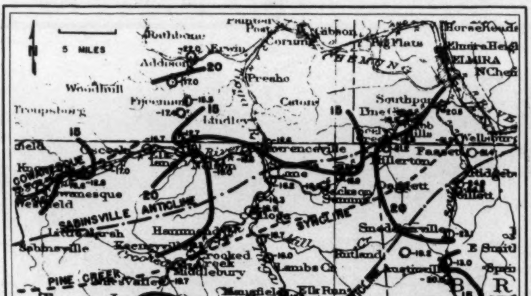


Fig. 2--Cross section of gravity anomaly, corrected for regional variations; points are projected along circular arcs onto a NW-SE line


5 MILES
Rathbone
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Freeman
Caton
Lindley
Southport
20
15
Osceola
Lawrenceville
Millerton
Knoxville
COWANESQUE
Westfield
SABINSVILLE ANTICLINE
SYNCLINE
Tioga
Jackson Summit
Daggett
Little Marsh
Hammond
Sabinsville
Keeneyville
Crooked Creek
Middlebury
Lambs Cr
Rutland
Austinville
E Smithfield
PINE CREEK
Mansfield
Elk Run
ANTICLINE
Sylvania
Mainesburg
Charleston
WELLSBORO
Ansonia
Cherry Flats
Covington
BLOSSBURG
Troy
Granville
Alba
Morris Run
Blossburg
T I O G A
B R

Fig. 3--Map showing structural axes and "residual" gravity after subtracting regional effect and anomaly due to sphere; geology after CATHCART [1934]

The observed anomaly was compared with that which would result from a vertical cylinder or sphere of diabase buried beneath the area using conventional methods [BOWIE 1924; HEILAND, 1940]. The best fit was obtained on the assumption of a sphere. Figure 2 shows the anomaly which would result from a sphere of density contrast 0.32 gm/cc at a depth of 47,500 ft and having a radius of 26,300 ft. The same anomaly would result from a 22,000-ft radius sphere of density contrast 0.55 gm/cc. The observed gravity values, corrected for a regional decrease of one mgal per 3.7 mi from west to east, are also plotted on the cross section, points lying southeast of the center of the anomaly being shown on the right, points to the northwest to the left. The agreement is as perfect as one can expect from such a simplified assumption, as any actual intrusive which exists would be more irregular than the assumed sphere. The anomaly could, of course, be caused by a more irregular structure of similar composition at shallower depth.

The regional gradient and the assumed anomaly were subtracted from observed values of gravity, and the remainder plotted as Figure 3. The location of the anticlinal and synclinal axes reported by CATHCART [1934] are shown on this map. No distinctive pattern can be recognized; so it is concluded that the observed anomaly probably results from a single intrusive unconnected with the main structural trends in the overlying sediments. Its maximum possible depth is so great that it is very likely entirely in the basement or nearly so.

Other materials than diabase or peridotite would be capable of causing such an anomaly. Salt, density 2.1 gm/cc, and anhydrite, density 2.9 gm/cc [BIRCH 1942, p. 24], have been encountered in the Salina formation in the Tioga gas field [FETTKE, 1950]. A lack of salt over part of the area or the presence of a cap of anhydrite could cause an anomaly of this shape. However, the quantity of either of these materials required to be absent or present to account for so large an anomaly argues against this explanation.

A similarly shaped anomaly appears on the gravity map by HAMMER [1938] in the vicinity of Bradford, Pa. The Bradford anomaly is located close to the Bradford oil field. The Tioga anomaly is near the Tioga gas field. If it could be established that there is some structural pattern not apparent at the surface which produces both the gravity anomaly and the petroleum traps, then gravity would perhaps provide a useful guide for further exploration work in northern Pennsylvania and adjoining regions.

Acknowledgment--The survey on which this article is based was performed by K. Vozoff, now with the Phelps-Dodge Corp., Douglas, Ariz., as a part of the requirements for the degree of Master of Science at The Pennsylvania State College. The complete thesis is on file in the college library.

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REDUCTION OF AIRBORNE MAGNETOMETER RESULTS

L. Hurwitz

Abstract--Reduction of observations obtained with the vector airborne magnetometer, Model 1A, is somewhat simplified by the computation of reduced (level-flight) angles. Aircraft swing data are analyzed by magnetic field components X, Y, Z rather than by elements D, H, Z. Similarly corrections for aircraft magnetism are applied to components, thus facilitating the application of punch-card processing methods.

Introduction--The U. S. Coast and Geodetic Survey has been cooperating with the U. S. Air Force in an airborne magnetic survey since 1949. The objective, equipment, operations, and general computing methods have been previously described [SCHONSTEDT and IRONS, 1953]. The Naval Ordnance Laboratory (NOL) developed the vector airborne magnetometer (VAM-1A) from the magnetic airborne detector (MAD) [RUMBAUGH and ALLDREDGE, 1949]. The purpose of this discussion is to describe some processing steps not previously given in published form.

Use of reduced angles--The basic equation for the X′ component of the combined magnetic field of the Earth and aircraft is [SCHONSTEDT and IRONS, 1953]

$$(X'/F') = \sin\alpha'\cos\beta'\cos P - \sin\beta'\sin P\sin R + \cos\alpha'\cos\beta'\sin P\cos R \quad \ldots\ldots \quad (1)$$

where the prime denotes that a quantity is affected by magnetism of the aircraft, and

F' = combined total magnetic intensity, Earth and aircraft, the only element or component of the field directly measured by the equipment

X' = axial component of combined field, Earth and aircraft, relative to vertical reference system

α', β' = two-minute averages of angles of attitude, fluxgates relative to aircraft

P, R = two-minute averages of angles of attitude, aircraft relative to a vertical pendulum

The reduced angles α'_r and β'_r, that would be recorded if P and R were both zero, are given to a sufficient accuracy for values of α' and β' less than 45° (dip greater than 45°) and for small P and R, by

$$\alpha'_r = \alpha' + P + R\sin\alpha'\tan\beta' \quad \ldots\ldots \quad (2)$$

$$\beta'_r = \beta' + R\cos\alpha' \quad \ldots\ldots \quad (3)$$

With these reduced angles, (1) reduces to

$$(X'/F') = \sin\alpha'_r\cos\beta'_r \quad \ldots\ldots \quad (4)$$

Similarly modified equations for (Y'/F') and (Z'/F') are

$$(Y'/F') = -\sin\beta'_r \quad \ldots\ldots \quad (5)$$

$$(Z'/F') = \cos\alpha'_r\cos\beta'_r \quad \ldots\ldots \quad (6)$$

Corrections for aircraft magnetism--The fundamental assumption regarding the effect of the magnetism of the aircraft is embodied in Poisson's equation [EVANS and SMITH, 1912]

$$X' = X + aX + bY + cZ + P \quad \ldots\ldots \quad (7)$$
$$Y' = Y + dX + eY + fZ + Q \quad \ldots\ldots \quad (8)$$
$$Z' = Z + gX + hY + kZ + R \quad \ldots\ldots \quad (9)$$

in which a to k are constant parameters depending on the soft iron of the craft, and P, Q, and R are constant parameters depending on the permanent magnetism of the craft.

When X′, Y′, Z′, and the parameters are known, then X, Y, and Z can be computed from

$$X = X' - a'X' - b'Y' - c'Z' - P' \quad \ldots\ldots (10)$$
$$Y = Y' - d'X' - e'Y' - f'Z' - Q' \quad \ldots\ldots (11)$$
$$Z = Z' - g'X' - h'Y' - k'Z' - R' \quad \ldots\ldots (12)$$

which are obtained from (7), (8), and (9) and where each primed parameter is approximately equal to the corresponding unprimed parameter. Exact expressions for each primed parameter, in terms of Poisson's parameters, are

$$\left.\begin{array}{l} a' = 1 - [(1 + e)(1 + k) - fh]/\Delta \approx a \\ b' = [b(1 + k) - ch]/\Delta \approx b \\ c' = [c(1 + e) - bf]/\Delta \approx c \\ d' = [d(1 + k) - fg]/\Delta \approx d \\ e' = 1 - [(1 + a)(1 + k) - cg]/\Delta \approx e \\ f' = [f(1 + a) - cd]/\Delta \approx f \\ g' = [g(1 + e) - dh]/\Delta \approx g \\ h' = [h(1 + a) - bg]/\Delta \approx h \\ k' = 1 - [(1 + a)(1 + e) - bd]/\Delta \approx k \\ P' = (1 - a')P - b'Q - c'R \approx P \\ Q' = -d'P + (1 - e')Q - f'R \approx Q \\ R' = -g'P - h'Q + (1 - k')R \approx R \end{array}\right\} \ldots\ldots (13)$$

where

$$\left.\begin{array}{l} \Delta = (1 + a)(1 + e)(1 + k) + cdh + bfg - (1 + a)\, fh - bd\,(1 + k) - c\,(1 + e)\, g \\ \Delta \approx (1 + a)(1 + e)(1 + k) - fh - bd - cg \end{array}\right\} \ldots\ldots (14)$$

Aircraft swings are made at different magnetic latitudes for the purpose of determining these parameters.

Swing analysis--Swing operations now consist of three passes on each of eight headings (nominal magnetic headings = 0°, 45°, 90°, . . . 315°). Actual headings need be only within about 15° of the nominal headings. This tolerance is made possible by application of successive approximation methods in the analysis. The successive approximation method is usually equivalent to graphical interpolation.

From swing data obtained at places where the Earth's magnetic field is fairly well known, the following mean deviations are computed for each of the eight mean headings

$$X' - X$$
$$Y' - Y$$
$$Z' - Z$$

These are analyzed by the standard method of least-square swing analysis, with the added successive approximation when required. This analysis yields five coefficients A to E for each component, indicated in the following

$$X' - X = A_X + B_X \sin \zeta + C_X \cos \zeta + D_X \sin 2\zeta + E_X \cos 2\zeta \ldots\ldots (15)$$

$$Y' - Y = A_Y + B_Y \sin \zeta + C_Y \cos \zeta + D_Y \sin 2\zeta + E_Y \cos 2\zeta \ldots\ldots (16)$$

$$Z' - Z = A_Z + B_Z \sin \zeta + C_Z \cos \zeta + D_Z \sin 2\zeta + E_Z \cos 2\zeta \ldots\ldots (17)$$

The method of analysis will not yield directly any higher order terms; such terms should not occur.

Swings in localities of different magnetic latitude will yield several values of each of the 15 coefficients indicated in (15) to (17). These data may be checked against the fundamental assumption of constant parameters and the parameters may be obtained as follows:

(1) The observed values of a B or C coefficient, plotted against H, should lie on a straight line through the origin. The slope of the line is a desired parameter.

(2) The observed values of an A coefficient plotted against Z should lie on a straight line. The slope and intercept of the line give two of the desired parameters.

(3) The observed values of a D or E coefficient should be small, and the average over several swings, irrespective of magnetic latitude, should be zero.

Typical D_Z and E_Z values for several swings, in cgs units, are

D_Z: -0.0001, -0.0004, 0.0000, -0.0002, -0.0003, -0.0002, 0.0000

E_Z: -0.0002, -0.0004, 0.0002, 0.0001, 0.0002, 0.0005, 0.0001

Typical values of coefficients, taken from a Tucson swing, are, in cgs units,

$A_X = 0.0016$ $A_Y = -0.0032$ $A_Z = 0.0010$

$B_X = 0.0035$ $B_Y = -0.0029$ $B_Z = -0.0021$

$C_X = 0.0032$ $C_Y = 0.0034$ $C_Z = -0.0006$

$D_X = 0.0002$ $D_Y = 0.0003$ $D_Z = 0.0000$

$E_X = -0.0006$ $E_Y = 0.0012$ $E_Z = 0.0001$

The origin of nonzero D and E coefficients may be random errors, or an index error in the angle β_r', or errors in the assumed field for the swing point.

Routine--On a routine basis, swings are hand-processed as fast as received. In addition, values of D′, H′, and Z′ at or near track intersections are hand computed. When the postseason calibrations are completed, index corrections and parameters are adopted, after which the processing is completed.

If punch-card processing is to be used for the bulk of the work, the basic data can be keypunched during the season. That leaves very little key-punching and hand work after the end of the season.

It is to be noted that normally D′, I′, and H′ need not be computed.

Acknowledgment--I am indebted to E. O. Schonstedt and H. R. Irons for their courtesy in supplying me with an advance copy of their paper.

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AIRBORNE MAGNETOMETER FOR DETERMINING ALL MAGNETIC COMPONENTS

E. O. Schonstedt and H. R. Irons

Abstract--The NOL vector airborne magnetometer Type 1A (VAM-1A), designed for measuring components of the geomagnetic field from aircraft, consists of a modification of the AN/ASQ-3A equipment employed for geophysical exploration by air. The VAM-1A continuously records the total intensity of the field and its direction with respect to vertical and horizontal coordinates established by a pendulum. The effects of accelerations of the aircraft on the vertical accuracy of the pendular reference are largely eliminated by averaging the magnetometer data over a period normally required for two phugoid oscillations of the aircraft. The operation of the magnetometer is limited to regions in which the magnetic dip exceeds 45°. The magnetometer is estimated to measure F, H, and Z to an accuracy of 200 gammas.

Introduction--The need for world-wide surveys of the geomagnetic field vector over the surface of the Earth has become increasingly urgent with each passing year. Since the destruction by fire of the nonmagnetic ship *Carnegie* in Samoa in 1929, very little magnetic surveying has been done at sea. Current magnetic charts of oceanic areas are made up to a large extent by extrapolating from old data. These charts are of questionable reliability because the change in the geomagnetic field over long periods of time cannot be predicted accurately.

It has long been recognized that aircraft would provide an excellent medium for making magnetic surveys. The chief advantages of aircraft are the speed with which large distances may be covered, the access they afford to remote regions of the Earth, and the fact that they are less magnetic than most seagoing ships.

Suitable instruments for conducting airborne surveys were not available before World War II. During the War, the saturable-inductor type magnetic airborne detector, conceived initially as a tool for the exploration geophysicist, was actually developed for the detection of submarines. It was not long until, with suitable modifications, it came into use in geophysical exploration. This instrument embodies the features which made possible the construction of an airborne magnetometer to measure the components of the geomagnetic field. Such a magnetometer for measuring components is generally referred to as a universal airborne magnetometer.

In view of the Naval Ordnance Laboratory's considerable experience in the development of magnetic airborne submarine detectors (the AN/ASQ-3 and AN/ASQ-3A magnetic airborne detectors (MAD) were developed cooperatively by the Naval Ordnance Laboratory and the Bell Telephone Laboratories. The AN/ASQ-3A system was modified by NOL and BTL for geophysical exploration and has been used extensively for this purpose by the U. S. Geological Survey), the Office of Naval Research sponsored at the Laboratory a program for the development of a universal airborne magnetometer. Under ONR sponsorship, the NOL vector airborne magnetometer Type 1A (VAM-1A) was developed. This instrument has been used by the U. S. Coast and Geodetic Survey and the U. S. Air Force in a cooperative survey project since 1949 [KELLER and Others, 1951]. The VAM-1A was described in an oral presentation before the 30th Annual Meeting of the American Geophysical Union.

General description of the VAM-1A--The VAM-1A is an enlarged and modified form of the AN/ASQ-3A magnetic airborne detector. This latter instrument is used for making continuous airborne measurements of the variation in the geomagnetic total intensity. The construction of the VAM-1A has consisted essentially of adding means to the geophysical version of the AN/ASQ-3A instrument for determining the direction of the geomagnetic field and for measuring more precisely the value of the absolute total intensity about which the variations are recorded. Since the AN/ASQ-3A equipment for geophysical exploration has been described adequately in the literature [FELCH and Others, 1947; RUMBAUGH and ALLDREDGE, 1949], its features will not be reviewed here.

The steps taken to construct the VAM-1A from the ASQ-3A geophysical instrument were essentially the following:

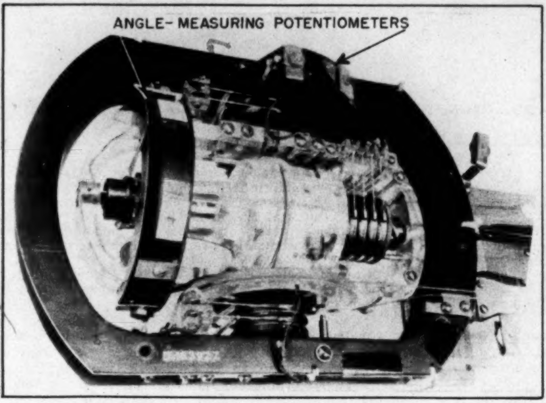

ANGLE- MEASURING POTENTIOMETERS

Fig. 1--Detector gimbal

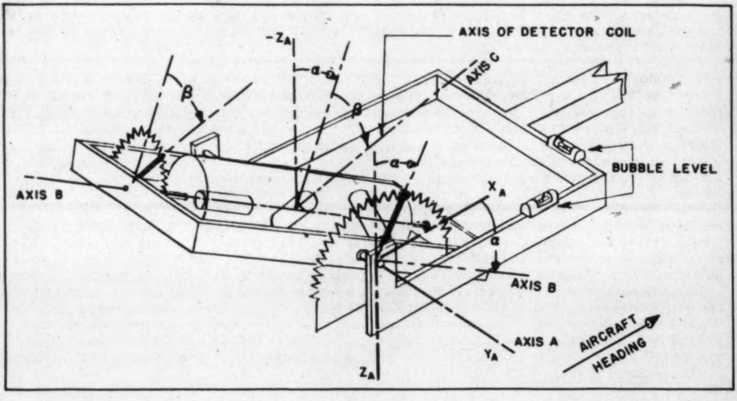

$-Z_A$
AXIS OF DETECTOR COIL
AXIS C
β
$\alpha-\alpha'$
β
$\alpha-\alpha'$
BUBBLE LEVEL
AXIS B
X_A
α
AXIS B
AXIS A
Y_A
Z_A
AIRCRAFT HEADING

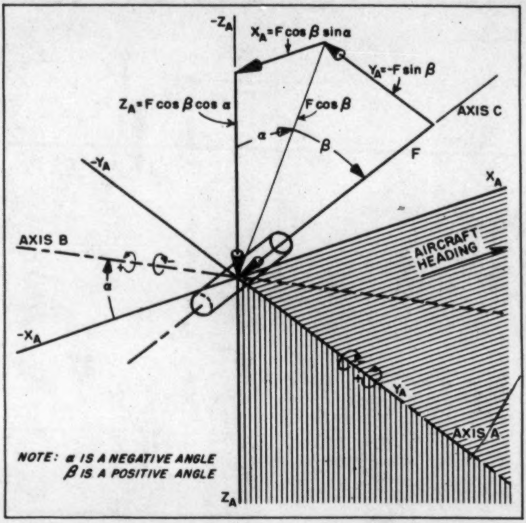
Fig. 2--Diagram of detector gimbal

(1) Modification of the field-measuring circuit to determine more accurately the absolute value of the total intensity.

(2) The development of means for measuring the direction of the geomagnetic field with respect to coordinate axes fixed to the aircraft.

(3) The development of apparatus and techniques for ascertaining the attitude of the aircraft coordinate axes with respect to vertical and with respect to a line representing the projection of the longitudinal axis of the aircraft on a horizontal plane.

One additional item, the true heading of the aircraft, is needed to determine the complete magnetic vector. True heading is obtained by a conventional method and hence the apparatus used for this purpose is not a part of the VAM-1A magnetometer development.



NOTE: α IS A NEGATIVE ANGLE
β IS A POSITIVE ANGLE

Fig. 3--Components with respect to coordinates of the aircraft

Modification of the ASQ-3A geophysical magnetometer to measure the absolute value of the Earth's total magnetic field intensity--A minor modification was made to the AN/ASQ-3A geophysical instrument in order to ascertain more accurately the absolute value of the total intensity of the Earth's magnetic field. In the 3A system a direct current is passed through the field measuring inductor to null out the greater part of the geomagnetic field therein. Variations in the total intensity about the base value established by this current are recorded on a strip recording instrument. The base-line value established by the inductor nulling current is determined from the setting of a three-decade resistor box and the voltage of an artificially aged battery. In order to determine the battery voltage accurately there was added to the circuit a precision resistor with taps for connecting it to a standard-cell potentiometer, with the aid of which the circuit is adjusted for the existing battery voltage before each flight and checked for drift after the flight is completed.

Measurement of the direction of the field with respect to the aircraft--One important feature of the AN/ASQ-3A system is that the gimbal-mounted inductor, which measures the total field intensity, is continuously oriented parallel to the geomagnetic field by a servo system. In the present application the detector mechanism is carried in the fuselage of the aircraft and not streamed from the aircraft in a bomb-like housing on the end of a long cable as is frequently done in geophysical exploration. The direction of the field can be determined, therefore, with respect to coordinate axes fixed in relation to the aircraft, by measuring the attitude of the detector inductor in its gimbal. Potentiometers (potential-dividing rheostats) mounted about the pivot axes of the gimbal mechanism of the detector head, illustrated in Figure 1, are used in the VAM-1A for this purpose.

As shown in Figure 2, the amount of angular rotation of the detector inductor about the outer axis, A, of the gimbal is referred to as angle α. The angular displacement about the inner axis, B, is angle β. Angle β is zero when the axis, C, of the detector coil is perpendicular to axis A. Angle α is zero when axis B lies in the plane determined by the two spirit levels mounted on the gimbal frame.

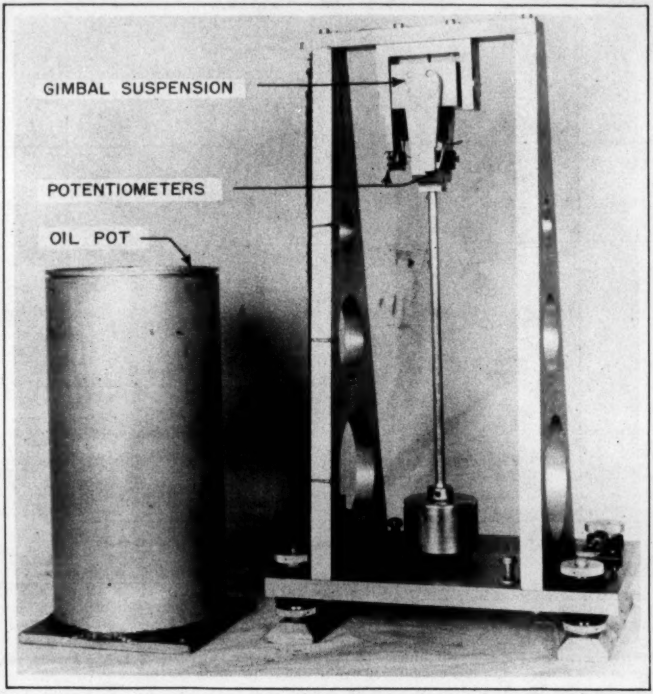


Fig. 4--Pendulum

The mechanism is installed in an aircraft in such a manner that axis A is placed substantially horizontal and perpendicular to the center line of the aircraft. Axis A forms the coordinate of the aircraft, designated Y_A, as shown in figure 2. Coordinate X_A is formed by the position of axis B when α is zero. X_A is positive in the direction of flight. Z_A is perpendicular to X_A and Y_A and is taken as positive in the downward direction to conform with geomagnetic convention by which the downward direction of the vertical component of the geomagnetic field is considered to be positive.

The components measured with respect to the aircraft as shown in Figure 3, are

$$X_A = F \cos \beta \sin \alpha \quad \ldots\ldots \quad (1)$$

$$Y_A = -F \sin \beta \quad \ldots\ldots \quad (2)$$

$$Z_A = F \cos \beta \cos \alpha \quad \ldots\ldots \quad (3)$$

A right-hand coordinate system is used in which the polarity of α and β are as indicated in Figure 3.

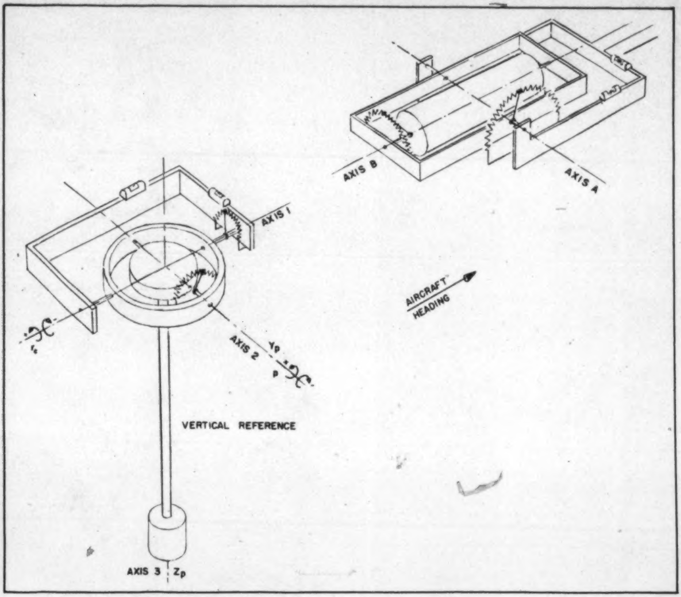


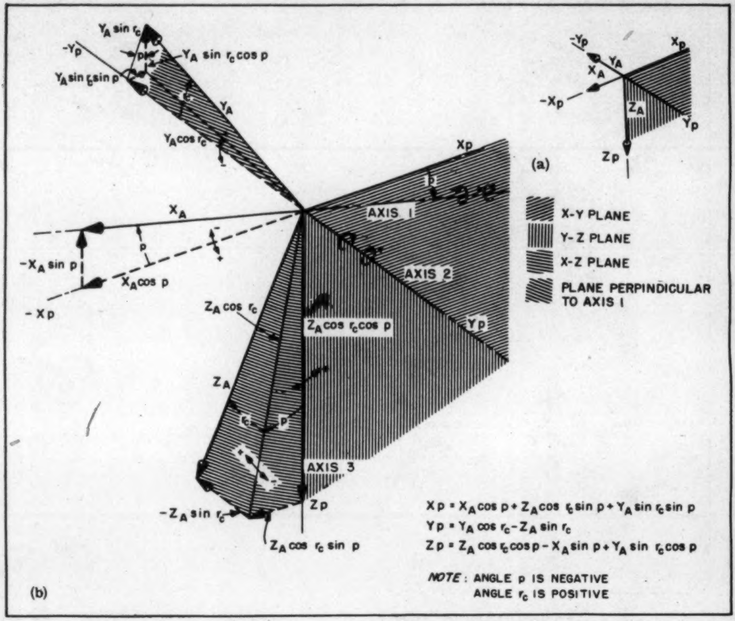
Fig. 5--Arrangement of the detector head and the pendulum in the aircraft

Measurement of the attitude of the aircraft coordinate system--The pendulum shown in Figure 4 is used for measuring the attitude of the aircraft coordinate system. Its gimbal-suspended bob is immersed in a viscous oil for damping purposes.

Figure 5 shows the relation of the pendulum to the detector gimbals when installed in an aircraft. The pendulum is oriented with its outer or fixed pivot axis, 1, parallel with the coordinate X_A of the aircraft. The inner pivot axis, 2, is held horizontal by the bob and will be parallel to the coordinate Y_A when the latter is horizontal. Spirit levels facilitate the leveling of the pendulum gimbal frame with respect to the magnetometer detector gimbal frame during installation.

Ignoring accelerations of the aircraft for the present, the vertical coordinate established by the pendulum, referred to as Z_P, is parallel to axis 3 of the pendulum arm. One horizontal coordinate Y_P is coincident with axis 2 and perpendicular to the direction of flight. The other horizontal coordinate, X_P, is perpendicular to Y_P and Z_P. Angle p is the displacement of the bob about axis 2, and angle r_c is the displacement of the bob about axis 1. When p and r_c are zero, components X_A, Y_A, and Z_A will be parallel to X_P, Y_P, and Z_P, respectively, as shown in Figure 6a. Figure 6b shows the relations when p and r_c are not zero.

The equations for the components measured with respect to the pendulum coordinates are included in Figure 6b. The component equations of Figure 6b are identical with (4), (5), and (6) given below, except that r has been substituted for r_c. Angle r is equal to r_c after the latter has been corrected for Coriolis acceleration. (Coriolis force will deflect a pendulum to one's right in the Northern Hemisphere and to one's left in the Southern Hemisphere when one faces in the direction of flight. The magnitude of the correction can be obtained from the back cover of the American Air Almanac of the U. S. Naval Observatory. The notation r_c indicates that the pendulum roll angle must be corrected for Coriolis acceleration.)



(a)
-Yp
Xp
YA
XA
-Xp
ZA
Yp
Zp
X-Y PLANE
Y-Z PLANE
X-Z PLANE
PLANE PERPINDICULAR TO AXIS I
YA sin rc
-Yp
YA sin rc cos p
YA sin rc sin p
p
rc
YA
YA cos rc
Xp
p
AXIS I
XA
-XA sin p
XA cos p
-Xp
AXIS 2
ZA cos rc
ZA cos rc cos p
Yp
ZA
rc
p
AXIS 3
-ZA sin rc
Zp
ZA cos rc sin p
Xp = XA cos p + ZA cos rc sin p + YA sin rc sin p
Yp = YA cos rc - ZA sin rc
Zp = ZA cos rc cos p - XA sin p + YA sin rc cos p
NOTE: ANGLE p IS NEGATIVE
ANGLE rc IS POSITIVE
(b)

Fig. 6--Components (a) with $p = r_c = 0$ and (b) with p and r_c not equal to zero

The correction of p for Coriolis acceleration will be negligible. The subscripts P of Figure 6b have been changed to "E" in (4), (5), and (6) to denote this modification. Hence,

$$X_E = X_A \cos p + Y_A \sin r \sin p + Z_A \cos r \sin p$$

$$= F (\cos \beta \sin \alpha \cos p - \sin \beta \sin r \sin p + \cos \beta \cos \alpha \cos r \sin p) \quad \ldots\ldots (4)$$

$$Y_E = Y_A \cos r - Z_A \sin r$$

$$= -F (\sin \beta \cos r + \cos \beta \cos \alpha \sin r) \quad \ldots\ldots (5)$$

$$Z_E = Z_A \cos r \cos p - X_A \sin p + Y_A \sin r \cos p$$

$$= F (\cos \beta \cos \alpha \cos r \cos p - \cos \beta \sin \alpha \sin p - \sin \beta \sin r \cos p) \quad \ldots\ldots (6)$$

Portions of the elements which comprise the magnetic field vector can be computed for a given point from (4), (5), and (6). The angle of inclination is

$$I = \sin^{-1} (Z_E/F) \quad \ldots\ldots (7)$$
$$= \sin^{-1} (\cos \beta \cos \alpha \cos r \cos p - \cos \beta \sin \alpha \sin p - \sin \beta \sin r \cos p)$$

The horizontal component, H, is

$$H = F \cos I \quad \ldots\ldots (8)$$

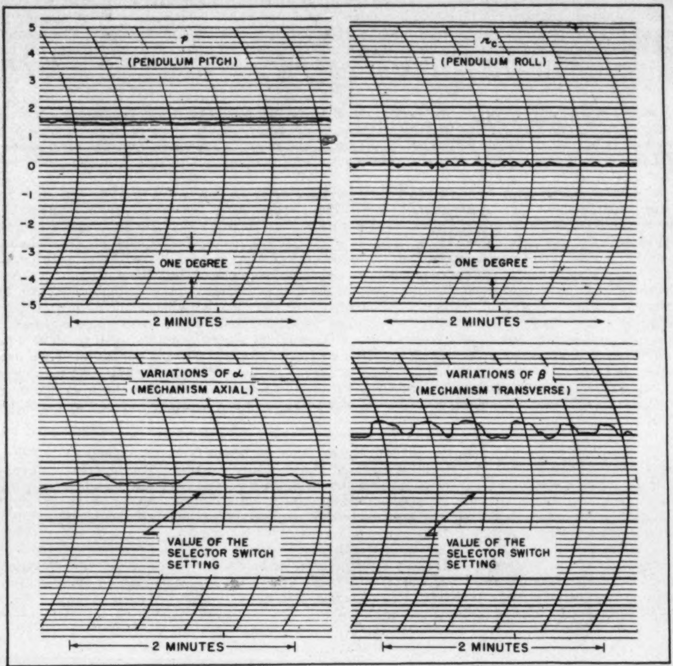


Fig. 7--Recorded variations of α, β, p and r_c

The vertical component, Z, is

$$Z = F \sin I = Z_E \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

The magnetic heading, MH, of the aircraft is

$$\begin{aligned} MH &= \tan^{-1} (-Y_E/X_E) \\ &= \tan^{-1} \frac{\sin\beta\cos r + \cos\beta\cos\alpha\sin r}{\cos\beta\sin\alpha\cos p - \sin\beta\sin r\sin p + \cos\beta\cos\alpha\cos r\sin p} \quad \ldots (10) \end{aligned}$$

The minus sign is associated with Y_E in (10) in order that the magnetic heading angle will agree with that obtained with a magnetic compass.

Equations (4), (5), and (6) are somewhat lengthy but consist of simple trigonometric relations. The computations are not difficult if a mechanical calculator is employed. Also, if the aircraft can be suitably leveled on the ground when the magnetometer is installed, the angles p and r may be so small that their cosines can be taken as unity. Sin r sin p usually can be considered to be zero.

With the additional knowledge of true heading of the aircraft, the magnetic vector for a given point can be defined completely. The U. S. Coast and Geodetic Survey and U. S. Air Force, in their joint survey project employing the VAM-1A, obtain true heading with a manually operated precision astro compass. A true heading value is obtained every five minutes by computing the average of a set of celestial readings taken over an interval of about two minutes. The magnetic vector is therefore computed for points along the flight path, the interval between points being the distance covered in five minutes of flight. This interval between points, however, can be varied as desired.

Angle measuring circuits--The variations of F, α, β, p, and r_c are continuously recorded on the strip charts of recording milliammeters. Records of variations of α, β, p, and r_c are shown on figure 7. The total values of F, α, and β are each measured by settings of selector switches in control units plus the variations about those settings, as recorded on the strip charts.

Figure 8 is a diagram of the circuit used for measuring angles α and β. The rheostat elements mounted about each of the gimbal axes of the detector head are excited from a 1250-cycle source, this frequency having the advantage of a negligible coupling with the 2000-cycle magnetic-field measuring signal produced in the inductors. Excited in parallel with each of the rheostat elements is a series of precision resistors. Each resistor has been selected so as to be proportional to the resistance of the corresponding five-degree segment of the rheostat element. A selector switch provides for connecting to any of the fixed resistors. The voltage developed between the rheostat wiper and the switch contactor is fed to a phase detector and amplifier and recorded on a recording milliammeter. The gain of the amplifier is adjusted so that a five-degree difference between the position of the rheostat wiper and the switch contactor will produce a full-scale reading on a zero-center recording milliammeter. To illustrate the operation of the bridge, assume that the wiper was displaced 22° from its zero position. This angle would be measured by setting the selector switch on 20° and the additional two degrees would be shown on the milliammeter. (The selector switch could be set also at 25° and minus three degrees would be recorded.)

The magnetometer will operate only in regions in which α and β do not exceed 45°. This, in general, would include areas in which the angle of dip is 45° or greater. The limitation in range was imposed by the structure of the potentiometers which prevented very much additional gimbal motion. The immediate need for the magnetometer did not anticipate surveying below 45° of dip, so the additional mechanical construction required to appreciably extend the range was not considered to be warranted.

Angles p and r_c are measured with a simpler form of bridge circuit in which direct current is used for excitation. No amplifier and phase detector are required. Inasmuch as these angles seldom exceed two degrees, the bridge is a nonadjustable type.

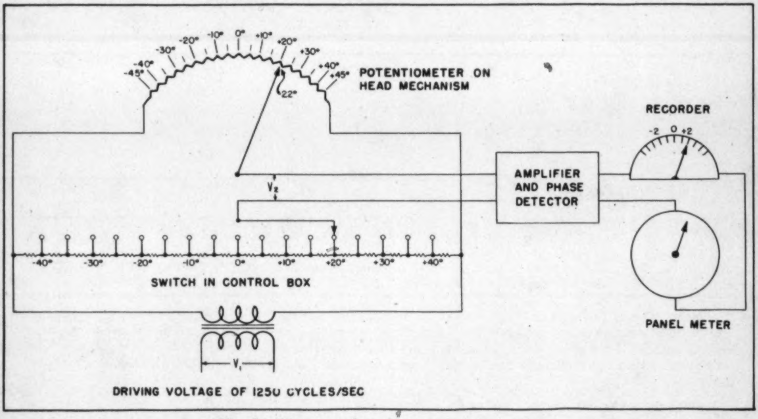


Fig. 8--Diagram of angle measuring circuit

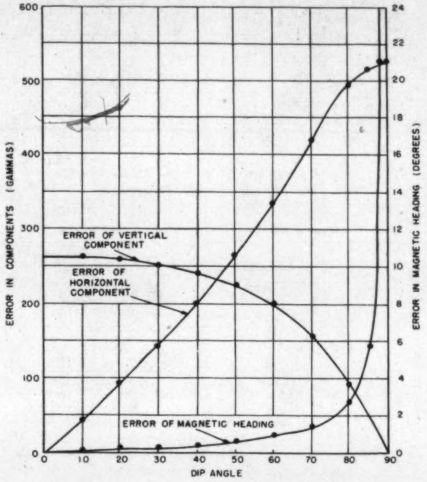


Fig. 9--Maximum error of measurement of vertical and horizontal components and magnetic heading due to one-half degree error of vertical reference

Problem of the vertical reference--The accuracy of the measurements made with a universal airborne magnetometer depends to a large extent upon the precision to which the vertical can be determined. Figure 9 shows that the errors in magnetic components due to an error of one-half degree in the vertical reference can be undesirably large. (The errors in H and Z are computed on the assumption that G, the local magnetic constant, is uniformly 30,000 gammas, whereas strictly they should be adjusted in proportion to G, where $G^2 = H^2 + 1/4\ Z^2$.) A pendulum is very sensitive to accelerations of the aircraft so that it is not suitable as an instantaneous vertical reference. Most of the accelerations during cruising flight are due to oscillations of the aircraft which are, generally speaking, of a periodic nature. The effects of these accelerations on the vertical accuracy of the pendulum are largely eliminated by averaging over a suitable interval of flight the angular data recorded by the magnetometer.

The most disturbing accelerations affecting the pendulum are those associated with the roll and pitch oscillations of the aircraft. For our purpose here, we will assume that these oscillations are periodic and undamped. The term "phugoid" was coined [LANCHESTER, 1908] from two Greek words to mean "flight-like." The phugoid consists of oscillations about the pitch axis accompanied by variations in the altitude of the aircraft. The time for one such oscillation of a B-29 aircraft is about 45 to 50 sec. The motions about the roll axis occur at a higher frequency. The period of the roll oscillations of a B-29 is roughly 1/3 that of the phugoid oscillations. These motions are nearly sinusoidal when time is considered as the independent variable.

The manner in which the phugoid oscillations affect the instantaneous vertical reference accuracy of a pendulum may be deduced from figure 10. This figure contains two simultaneous recordings of the pitch motion of a B-29, one obtained with a gyro vertical and the other with a pendulum. The gyro record shows the angular amplitudes of the oscillation of the aircraft but the pendulum record is essentially a straight line. These records demonstrate that the bob of the pendulum oscillates in space in the direction of flight to a large extent as if it were rigidly secured to the aircraft. (The record shown is for a flight in which the oscillations were larger than those normally obtained.)

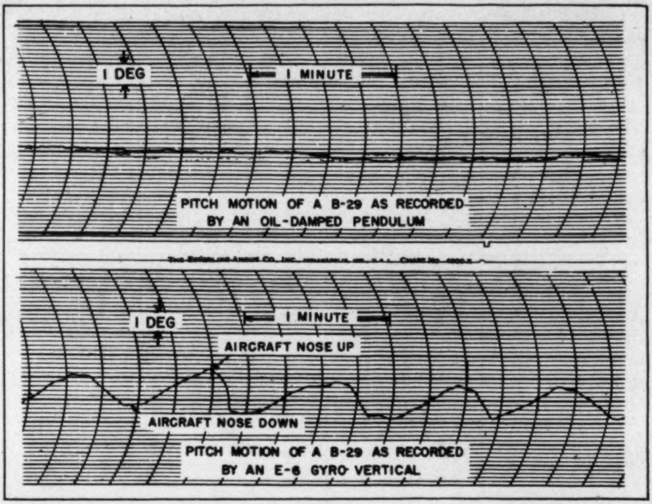


Fig. 10--B-29 aircraft pitch motion as measured by a pendulum and a gyro vertical

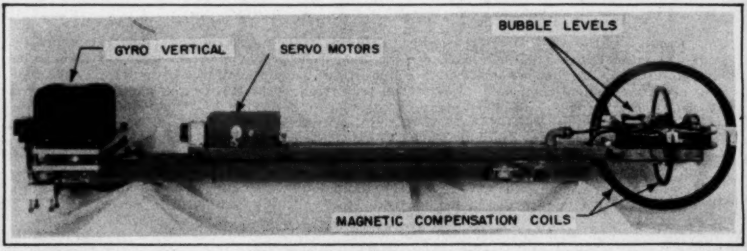


Fig. 11--Detector head

The pendulum performs in the roll direction in a similar fashion. This fact may be seen by referring to Figure 7 again. The recording of the roll angle of the pendulum is also essentially a straight line if we disregard the high-frequency oscillations which are due to the aircraft's yaw motion. (The yaw motion appears because the pendulum was located about 40 feet to the rear of the center of gravity of the aircraft.) The flight during which these recordings were obtained took place in a region of high dip, with the consequence that the variations of α and β are respectively representative of the pitch and roll motions of the aircraft.

It is apparent, then, that the pendulum oscillates in space in the roll and pitch directions at the frequencies and amplitudes of the roll and pitch motions of the aircraft. In cruising flight in smooth air, the pendulum motions are centered about a substantially vertical line. The average orientation of the pendulum axis in the pitch direction over one phugoid oscillation during such flight will provide a satisfactory measure of vertical in the plane of pitch. The same is true for an oscillation in the plane of roll provided a correction is made for the deflection of the pendulum due to Coriolis acceleration. The magnetometer's vertical, therefore, is determined by averaging the orientation of the pendulum axis over a suitable interval of flight.

The interval employed is the average time for two phugoid oscillations. If a single cycle of pitch motion were used for the interval, one could not be assured that an integral number of roll oscillations would be obtained during the interval and the error resulting may be undesirably large. By employing the time for two phugoid oscillations, the residual error caused by not having an integral number of roll oscillations has been found to be acceptably small. A fixed interval is used and no attempt is made to select periods in which precisely two cycles occur. This makes the process of analyzing the data simpler and more practical, for actually the aircraft oscillations during smooth flight are not very regular.

Other aspects of aircraft flight must be considered in the evaluation of a pendulum as a vertical reference. There will be some turns requiring such a long interval that their effect cannot be eliminated by the averaging process. During normal cruising such turns will not usually produce a serious error. At 320 km/hr (200 mi/hr), a turning rate of about 2/3 degree per minute is required to deflect the pendulum by 0.1 degree. Modern automatic-pilot systems such as those used on large bombers are capable of keeping on a straight course well within this rate. This has been substantiated for the B-29 with the records obtained with the directional gyro of the VAM-1A magnetometer.

A change of speed of 7.2 km/hr (4.5 mi/hr) in two minutes will result in a vertical reference error of 0.1 degree. The change of speed considered is that superimposed on the one resulting from the phugoid oscillation. An aircraft operating in smooth air under constant throttle should not change its average speed over a two-minute interval by that amount.

Accelerations of the air masses have been estimated [ROBERTS, 1950] to result in pendulum errors of two minutes of arc or less for general survey flight conditions. Corrections of the roll record for Coriolis acceleration must be made as mentioned previously.

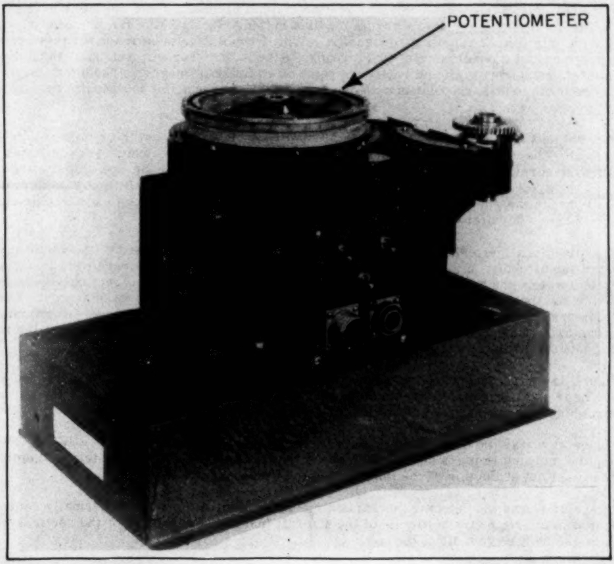


Fig. 12--Modified directional gyro of A C-1 auto-pilot system

An average value for each of the angles α , β , p, and r_c is obtained for the interval by manually scaling the recorder tapes. These average angular values (with average r used in place of average r_c), together with a figure for the total magnetic field intensity, are employed in (4) through (10). The components obtained with these equations are taken to represent the Earth's magnetic field vector at the midpoint of the interval.

It is preferable to employ in these equations the magnitude of the total intensity recorded at the midpoint of the interval rather than the average of the total intensity occurring during the interval. This is not particularly important but it is worth mentioning for it involves less work to use the midpoint value. During 100 seconds, an aircraft flying at 320 km/hr (200 mi/hr) will cover a distance of about 8.9 km (5.6 mi). The vector computed for the midpoint of this interval then represents a form of average of the vector for the interval. If the Earth's magnetic field varies nonlinearly over this distance, the vector computed for the midpoint will be slightly in error. This error has been found to be smaller if the midpoint value of total intensity is employed in the equations rather than an average value. In either case the inaccuracy is not large for surveys made at high altitudes (3 km or 10,000 ft or more) and for chart-making purpose it is of no consequence.

Corrections for magnetic fields of the aircraft--Most aircraft possess sufficiently large magnetic fields that these fields must be dealt with in some manner for inboard installations of magnetometers. An attempt to compensate for the magnetic fields of a B-29 by passing direct currents through three mutually perpendicular coils mounted about the detector inductor was not completely satisfactory because of the presence of induced magnetic fields. Induced fields can be compensated for by placing various suitable shapes and sizes of permeable material in the vicinity of the magnetometer detector mechanism. These materials create fields at the detector inductor which oppose those of the aircraft. This becomes an involved process and was not attempted for the VAM-1A installation.

The U. S. Coast and Geodetic Survey preferred to determine corrections for aircraft magnetism to be applied to all the components obtained in processing the magnetometer data. The U. S. Coast and Geodetic Survey has evolved a routine method for making the corrections [HURWITZ, 1953]. The corrections are derived from the data obtained by swinging the aircraft at two locations having different but known geomagnetic fields. Swings have been made for this purpose over or near the magnetic observatories at Fairbanks, Alaska, and Tucson, Arizona. Each swing consists of eight runs over a ground reference point on equidistant magnetic headings. Several swings are made over each point in order to improve the accuracy of the results by averaging the data.

General description of the VAM-1A components--A view of the detector mechanism is shown in Figure 11. The rings mounted about the detector gimbal are those which were intended for compensating the permanent magnetic fields of the aircraft. The unit at the end opposite the detector gimbal is the gyro vertical. Its purpose was to study aircraft motion. It is now seldom used. The box between the gimbal mechanism and gyro houses the two servomotors which orient the detector inductor parallel with the geomagnetic field.

The directional gyro shown in figure 12 provides a continuous record of the variations in the heading of the aircraft. Intervals during which the turning rate of the aircraft seriously affected the vertical-reference accuracy of the pendulum can be noted from the directional-gyro record. The device consists of a modified directional gyro used with a C-1 auto-pilot system. Directional variations are measured by means of a potentiometer (potential-dividing rheostat) mounted about the cardan axis of the gyro. The rheostat is incorporated in a circuit somewhat similar to that used for measuring the α and β angles.

Figure 13 shows most of the apparatus comprising the magnetometer. Not included are the detector head and recording milliammeters. The cross-hatched arrows indicate the portion of the gear which is a normal part of the AN/ASQ-3A equipment.

Figure 14 shows the control panel and recording instruments installed in a B-29. The recorders are mounted in pairs and faced in opposite directions so that their stray magnetic fields largely cancel out at the site of the magnetometer head.

Figure 15 shows the detector mechanism mounted in an insulated and thermally controlled box located in the rear center portion of the aircraft fuselage. A portion of the vertical-reference pendulum can be seen just aft of the box.

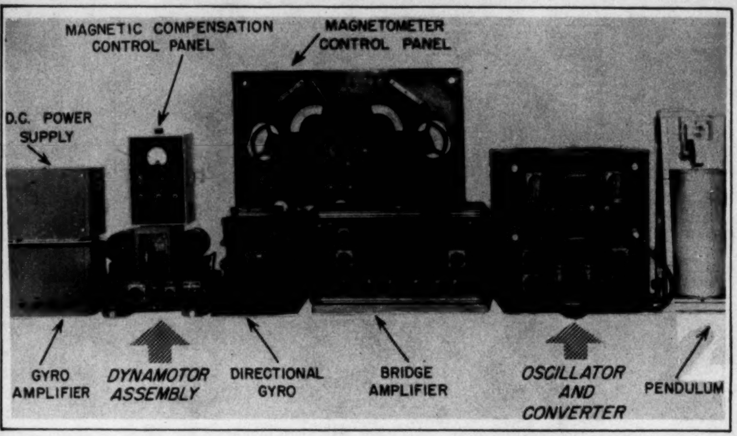

MAGNETIC COMPENSATION CONTROL PANEL
MAGNETOMETER CONTROL PANEL
D.C. POWER SUPPLY
GYRO AMPLIFIER
DYNAMOTOR ASSEMBLY
DIRECTIONAL GYRO
BRIDGE AMPLIFIER
OSCILLATOR AND CONVERTER
PENDULUM

Fig. 13--View of the electronic and control units

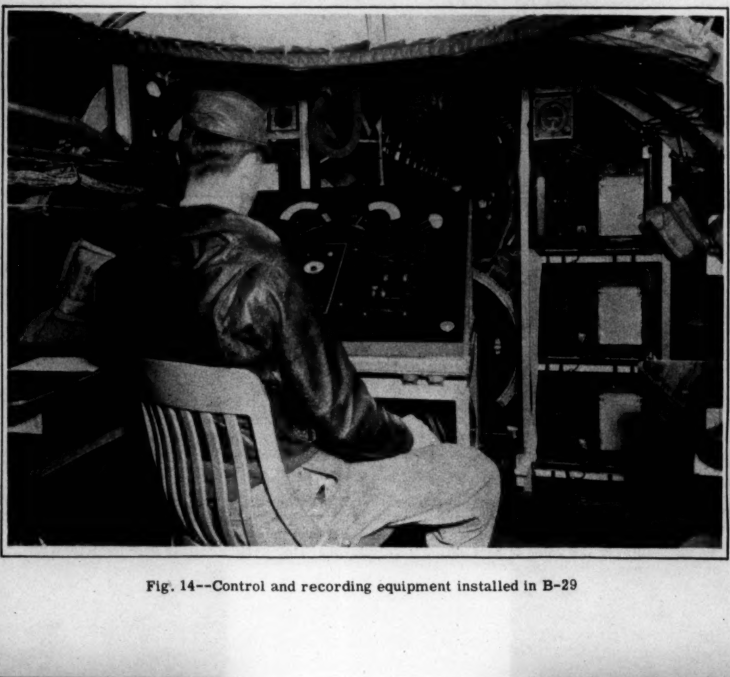


Fig. 14--Control and recording equipment installed in B-29

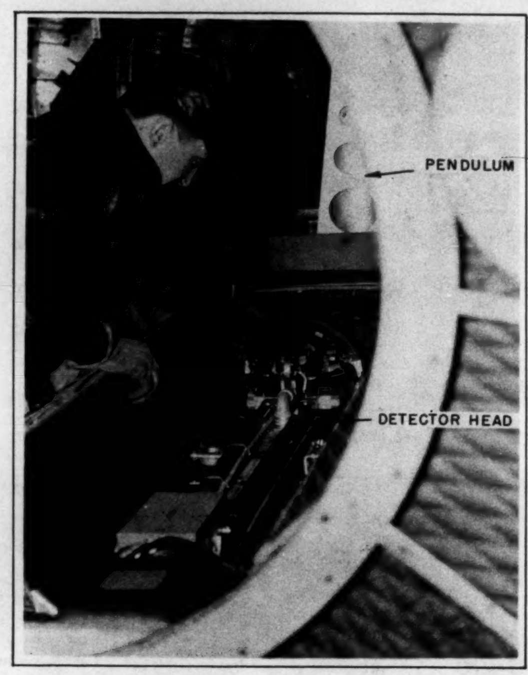


Fig. 15--Detector installation in B-29

Performance of the VAM-1A magnetometer--The evaluation of the performance of an airborne magnetometer for measuring components of the Earth's magnetic field is not a simple problem. One way is to compare airborne measurements with the values printed on magnetic charts. This method is not entirely satisfactory because the charts cannot show as much of the local detail as the airborne measurements. The probable error for any given point on the charts published by the U. S. Coast and Geodetic Survey is stated to be 300 gammas for the horizontal component and one-half degree for the angles of declination and dip. The probable error of the vertical component is estimated to be somewhat larger [DEEL and HOWE, 1948].

Another method of evaluation is to fly a number of times over a site for which the magnetic-field vector is known. The point selected should be in an area free from intense magnetic anomalies, so that the error introduced by not traversing directly over the point each time will be small. Preferably the flight should be made at three to six km (10,000 to 20,000 ft) to simulate actual survey operation.

The ideal conditions for such measurements are not easy to achieve. To conduct a good test, sufficient time should be allowed for approaching the point so that the aircraft will have settled down to optimum flight performance. A long approach run increases the difficulty of navigating the aircraft over the point without changing its course. This is particularly true for flights at high altitudes.

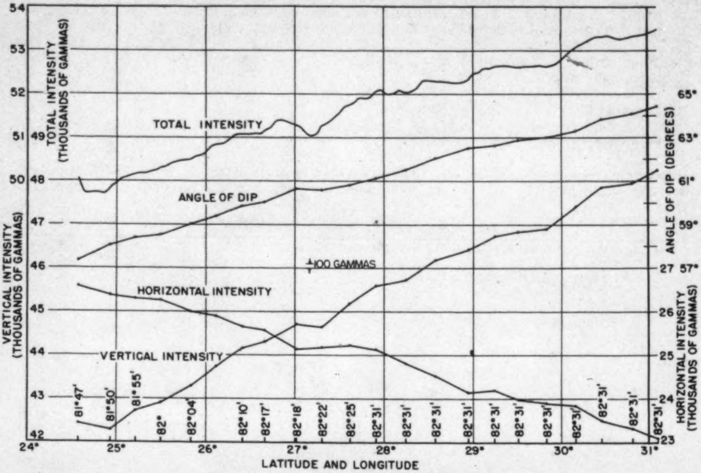


Fig. 16--Airborne measurements with universal magnetometer, October 21, 1949

In view of the uncertainties involved in this evaluation problem, precise performance figures cannot be stated. It is our understanding that the U. S. Coast and Geodetic Survey now estimates on the basis of their experience with the instrument that under average flight conditions H, Z, and F are measured with the VAM-1A to an accuracy of about 200 gammas, though this may include some effect of the noninstrumental factors already mentioned.

The results of a flight made during the shakedown period of the installation of the magnetometer in a B-29 are shown in figure 16. The flight line extended from Key West, Florida, to just north of the Florida-Georgia boundary. The record of the total magnetic field intensity is a continuous one. The vertical and horizontal components and angle of dip were computed for points with a spacing corresponding to five minutes of flight. Some idea of the performance of the magnetometer may be obtained by comparing the variation of the computed elements with the variations in the plot of the total magnetic field intensity.

Acknowledgment--This manuscript is an abridged form of one presented before the International Association of Terrestrial Magnetism and Electricity, at Brussels, Belgium, in August, 1951.

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Transactions, American Geophysical Union Volume 34, Number 3 June 1953

EXPERIMENTS WITH WINDSHIELDS FOR PRECIPITATION GAGES

C. C. Warnick

Abstract--Under cooperative encouragement from several Federal agencies, the Engineering Experiment Station of the University of Idaho has been studying the principles, development, and use of high-altitude precipitation gages. A low-speed wind tunnel has been used to study the effect of wind on the catching characteristics of model storage precipitation gages. A snow storm was simulated with sawdust, and various gage designs without windshields and with different type windshields were studied. Special techniques with photography were used to evaluate the value and improvement in performance of various windshield designs. Field studies have also been conducted at two remote mountain locations on prototype gages and shields similar to those studied in the laboratory. Results indicate reductions in catch due to the action of winds, and new shields proposed for use are showing an improvement in the consistency of catch both in studies in the wind-tunnel and in the field.

Introduction

Late in 1948 the Engineering Experiment Station of the University of Idaho was invited by representatives of the U. S. Bureau of Reclamation to conduct research on the development and use of high-altitude precipitation gages and windshields for these gages. The project was pointed up by the need for improving runoff forecasts. Recent floods and an accelerated program for the development of water resources have contributed in focusing closer attention to the problems of runoff forecasting and river regulation. Improved precipitation measurement records must be provided to insure better forecasts. The particular purpose of the program at the University of Idaho is to study the performance of existing gages and try to improve the accuracy and consistency of the precipitation catch by improving windshield designs.

Previous studies

It has long been recognized that winds have considerable influence on the catch of various types of precipitation gages. BROOKS [1938] concluded that unshielded gages can be deficient in catch by five to 50 pct or more, the higher deficiencies occurring in cases of snow measurements made in windy locations. ALTER's [1937] studies with shielded and unshielded gages likewise indicated that wind currents tend to decrease the amount of precipitation a gage will catch. Earliest use of a shield to correct for the influence of the wind might be credited to Joseph Henry of the Smithsonian Institution in 1853. About 1879 F. E. Nipher made a notable contribution with his trumpet-shaped metal shield which was fastened directly to the gage. This widely accepted shield gives good results when measuring rainfall, but it is unsatisfactory in the measurement of snowfall at unattended gages because of the tendency for snow to collect on the flat top of the shield and either fall into the gage or bridge over the gage orifice. By 1937, J. C. Alter had developed the Alter-type shield which is especially adapted to the measurement of snowfall and is at the present time being widely used. The individual baffles of the Alter shield are designed to prevent the collection of snow on the shield and gage. In this respect the shield is fairly successful, although some difficulty is still experienced with sleet and ice freezing to the assembly.

Testing program

Work on this project (Special Research Project 17) has been carried out in two phases; first, a laboratory study of scale models and shapes in a specially constructed, low-speed wind tunnel; and second, actual field tests at mountain locations.

Air-flow pattern study--Under the laboratory program a wind tunnel was constructed (see Fig. 1) to investigate air-flow patterns around models of various gage-and-windshield shapes and combinations. Two ships' ventilating fans are the wind source. These fans discharge air into a diffuser section and then through a diverging section into the tunnel throat. The throat is four by four feet in cross section. A honeycomb baffle system in the throat just forward of the test section cuts down turbulence and provides a relatively smooth flow of air. Variable speed fans provide a range of wind velocities in the tunnel up to 15 mi/hr. The test section is located

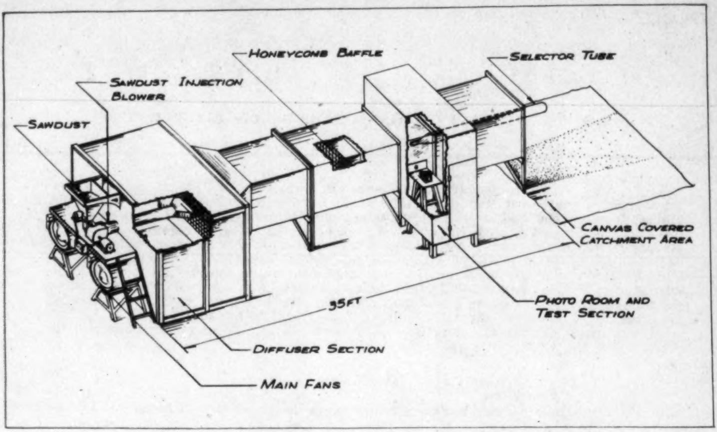


Fig. 1--Schematic drawing of low-speed wind tunnel used to study model precipitation gages under simulated snowstorm conditions

about ten feet from the open end of the tunnel in a light-tight room. A glass top and side panel are provided in the test section to give a means for observing, lighting, and photographing the models being tested.

Sawdust was injected into the airstream of the tunnel to define the air-flow patterns and was also used as artificial snow in studying the quantitative catch of the model gages. In Figure 1 a cutaway in the tunnel shows how this sawdust was fed from a hopper with controlled feed into a separate blower and through an injector tube equipped with vanes and splitters to give a uniform distribution of sawdust particles as they flowed into the throat section.

A jet of smoke was also used to study air-flow patterns. Titanium tetrachloride vapor introduced into the moist air passing through the tunnel produced a dense white smoke, titanium dioxide, which defined the air-flow pattern.

On a very cold day (about -17° F) in January, 1952, it was possible to blow actual snow through the tunnel. The snow used was a very dry, low-density snow. Figure 2 shows a picture of an unshielded gage with the three different methods used to define the air-flow patterns. Pictures here indicate why there is a deficiency in catch during a snowstorm when there is a wind blowing. Note the tendency for the path lines of the sawdust particles, smoke, and actual snow to blow upward owing to updrafts along the elements of the gage. Various windshield shapes and designs were tested in the wind tunnel to get an improved air-flow pattern over the gages. The method of mounting the gage and windshield is shown in Figure 3, a photograph taken through the glass wall of the wind tunnel. Figure 4 is a group of photographs illustrating the air-flow behavior around a few of the unsatisfactory designs tried. Figure 5 shows the air-flow pattern around three of the more satisfactory windshields. The swinging baffle type of shield proved to give the most encouraging air-flow pattern. Note that the bottom two photographs in Figure 5 show the path lines continuing downward in a normal manner as the "sawdust snow" passes over the gage orifice. Half-scale model gages used in the tests were of four basic types; Sacramento storage gage, Standpipe storage gage, Stevens Type Q-12 recording gage, and a Standard eight-inch diameter can gage. When a particular shield combination showed promise of improvement in the air-flow condition, a further test was made of the catching characteristics of the gage.

Comparative catch study--To provide a more quantitative means of comparing the performance of different gage-and-shield combinations, the models were tested in an artificial snowstorm. Sawdust was injected into the tunnel at a controlled rate, and the amount of sawdust caught in the gage

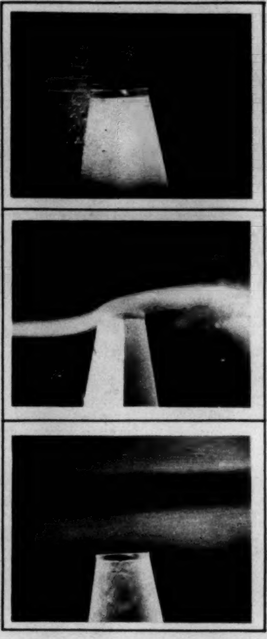


Fig. 2--Air-flow patterns around top of model Sacramento precipitation gage; (a) blowing sawdust, (b) titanium dioxide smoke, (c) actual snow

was carefully weighed. A typical run consisted of allowing 15 kg of finely divided "sawdust snow" to blow through the tunnel at a fixed rate such that it required 20 minutes to complete a test. The amount of sawdust snow collected in the gage compared to the catch of other gage-and-shield combinations became a useful measure of the effectiveness of the particular combination. Hundreds of such tests have been made. Early results indicated the swinging baffle shield to be superior, and much of the latest work has been concentrated on improvement of the old Alter design. Data presented under Results indicate the value of these tests.

Theoretical true-catch study--Because it is undoubtedly possible to overshield a gage, a means was devised for determining the theoretically true catch of sawdust snow that should be falling through an imaginary horizontal area equal to the area of the four-inch diameter orifice of the model gage. A selector tube and a special photographic arrangement was used in this series of tests. The selector tube was a long, thin-walled metal tube open at both ends (see Fig. 1). The forward end of the tube had a diameter of about 1 1/2 inches. From the forward end the tube diverges gradually to a diameter of about six inches. Owing to the increase in cross-sectional area, the wind speed inside the tube was reduced sufficiently so that all the sawdust snow was dropped inside the tube. The amount of sawdust caught during a given period of time could then be determined by weighing the sawdust in the selector tube. The selector tube was streamlined so that it caused no noticeable disturbance of the air-flow pattern and was always positioned so that it sampled the sawdust passing through the tunnel just at the height of the model gage's orifice. Reference to Figure 4 will show that in all these tests the direction of the undisturbed particles of sawdust is downward in the direction of flow owing to the action of gravity. Recognizing that this drift angle was consistent and duplicated, a phenomena commonly found with falling snow, a study was made of the drift angle and the particle velocity. With this information it was possible to relate the catch of sawdust going through a unit vertical area (that measured by the selector tube)

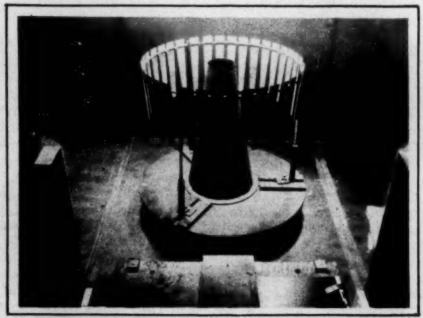


Fig. 3--Model precipitation gage with windshield mounted in wind tunnel ready for comparative catch test to be conducted (modified Alter I windshield)

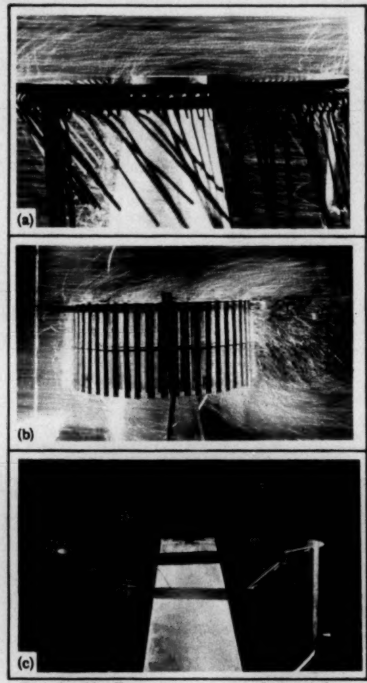


Fig. 4--Air-flow patterns around unsatisfactory gage-and-shield combinations; (a) hanging wire windshield, (b) snow-fence windshield, (c) floating-ring windshield

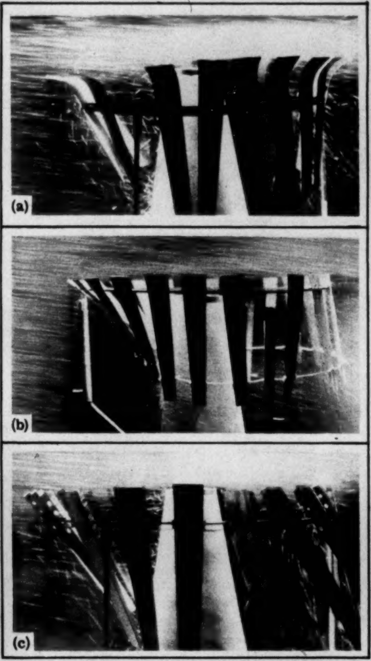


Fig. 5--Air-flow patterns around a few of the more satisfactory gage-and-shield combinations; (a) Idaho Type-I windshield, (b) standard Alter windshield, (c) modified Alter-II windshield

to the sawdust passing through a unit horizontal area.

The photographic setup used for this part of the testing program is shown in Figure 6. All this equipment was housed in a light-tight room. A four- by five-inch Speed-Graphic camera was used to take the photographs. The drift angle and velocity of the sawdust particles were defined by taking a photograph through the rotating wheel shutter against a gridwork background. This grid was scribed on a very thin sheet of metal mounted vertically in the tunnel as shown in Figure 7. Lighting was provided by means of synchronized flash bulbs in a special reflector (see Fig. 6). The rectangular reflector had double slits at the bottom in order to limit the width of the zone lighted. The width of this zone was about equal to the diameter of the gage orifice. By keeping the lighted zone narrow, and by using a low "f" setting on the camera to limit the depth of field, it was possible to obtain a photograph that showed only the sawdust snow immediately in front of the grid at the position of the orifice of the gage.

The rotating wheel shutter allowed light to get through to the camera only when one of the holes was in front of the lens of the camera, and as a result, the path lines of the sawdust particles appear as a series of dashes on the photograph. This is illustrated in Figure 8. Actual length of the dashes was found by comparing with the known distances on the gridwork. The dash length represents the distance the particle traveled while a hole of the rotating shutter was in

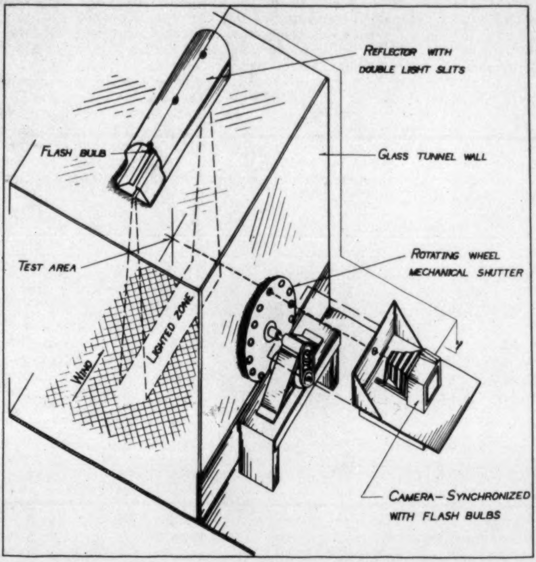

REFLECTOR WITH DOUBLE LIGHT SLITS
FLASH BULB
GLASS TUNNEL WALL
TEST AREA
ROTATING WHEEL MECHANICAL SHUTTER
LIGHTED ZONE
WIND
CAMERA-SYNCHRONIZED WITH FLASH BULBS

Fig. 6--Schematic drawing of special photographic setup used to determine the theoretically true catch of model precipitation gages

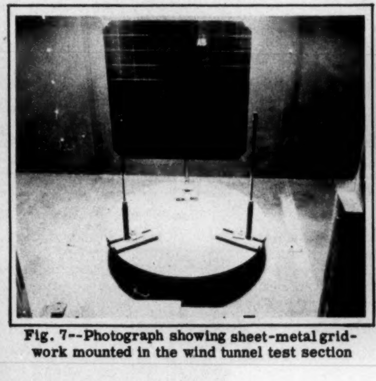


Fig. 7--Photograph showing sheet-metal gridwork mounted in the wind tunnel test section

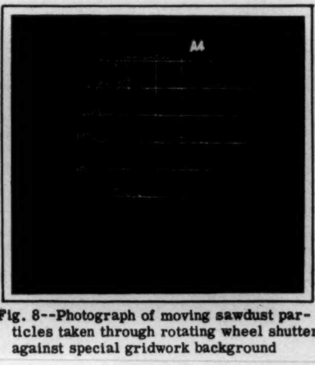


Fig. 8--Photograph of moving sawdust particles taken through rotating wheel shutter against special gridwork background

front of the camera. Hence, knowing the length of the dashes, number of holes in the shutter, and the rotational speed of the shutter wheel, the particle velocity was found. The average drift angle of the particles was scaled from the photograph. Using this angle and the cross-sectional area of the selector tube orifice, the effective catching area of the selector tube orifice was computed. This is the projected area perpendicular to the path line of the sawdust snow. The drift angle likewise defines the effective catching area of the horizontal gage orifice. The ratio of the weight of a true catch for the gage to the weight of a true catch for the selector tube should be the same as the ratio of the effective catching area of the gage to the effective catching area of the selector tube. The Results section of this paper gives data comparing the true catch with the actual catch of different model gages. It should be realized that the sampling of the sawdust discharge with the selector tube, the photographing of the undisturbed particle paths against the gridwork, and an actual test of the amount of sawdust snow caught by a model gage, followed systematically in order at the same setting for wind speed and the same rate of injection of sawdust to allow direct comparisons to be made.

Table 1--Descriptive information on experimental gages

Gage (1)	Location (2)	Type of gage (3)	Type of shield (4)	Type of support (5)
1	Mullan Pass	Stevens type Q-12 recorder	Standard Alter	20-ft, 4-legged tower
2	Mullan Pass	Sacramento storage gage	Standard Alter	15-ft, 3-legged tower
3	Mullan Pass	Standpipe storage gage	Standard Alter	18-ft standpipe
4	Mullan Pass	Sacramento storage gage	Ring type (1948-51) Mod. Alter I (1951-)	15-ft, 3-legged tower
5	Mullan Pass	Standpipe storage gage	Idaho Type I	18-ft standpipe
6	Mullan Pass	Sacramento storage gage	No shield (1949-51) Mod. Alter II (1951-)	15-ft, 3-legged tower
7	Mullan Pass	Sacramento storage gage	Idaho Type II	15-ft, 3-legged tower
8	Priest River Experimental Forest	Sacramento storage gage	Idaho Type II	15-ft, 3-legged tower
9	Priest River Experimental Forest	Weather Bureau standard 8"-gage	Idaho Type II	8-ft, 2-legged timber support

Field experiments--A plot containing seven experimental gages is located at Mullan Pass, Idaho, and two gages have been installed on Gisborne Mountain in the Priest River Experimental Forest. Table 1 gives information on the types of gages installed. The Mullan Pass station is at an elevation of 6000 ft and is situated on a ridge where there is normal exposure to wind. Figure 9 shows a group of these field gages at Mullan Pass. Observations at this station are made by personnel from a nearby Civil Aeronautics Administration Station. The recorder gage at this station has been inoperative much of the time, and the standpipe gages have frozen solid during part of the season, so the continuity of some of the records has been destroyed. At this station an attempt has been made to correlate the precipitation catch of particularly heavy storms or storm periods with the snow that falls on the ground near the gages. At the beginning of a storm period, gage readings were taken and a canvas-covered board was set flush with the old snow surface. Immediately after the storm, an eight-inch diameter snow tube was pushed into the snow that collected on the snow board, the weight of the snow was determined, and measurements were made of the precipitation caught in the gages to allow a comparison to be made.

The Gisborne Mountain station is located at an elevation of 5500 ft on the southwest slope of the mountain. Because rime ice conditions are bad in this vicinity, this location is an excellent place to study the gages and shields under extreme exposure conditions. At this location the Forest Service has several other gages in operation and their personnel has made all the observations. In addition, two improved experimental windshields were sent to the Weather Bureau at Silver Springs, Maryland, for testing at a research station in operation at that location.

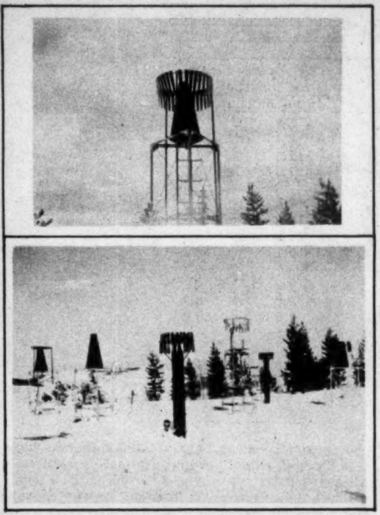


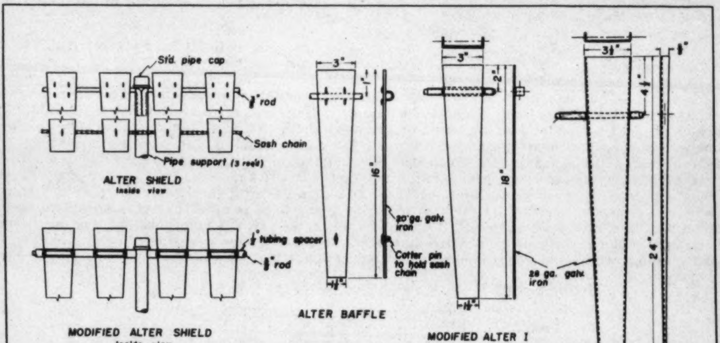
Fig. 9--Experimental precipitation gages at Mullan Pass Testing Plot; (a) Sacramento storage gage with modified Alter-I windshield, (b) standpipe storage gage in the foreground with Idaho Type-I windshield

Results

Results from the model study in the laboratory on comparative catch, indicate direct improvements can be expected in the performance of windshielded precipitation gages. Table 2 shows the comparative catch of a number of the combinations. From these studies two basic designs have been recommended for use and further field testing. Figure 10 is a drawing giving dimensions of the two proposed new shields and also data on a standard Alter shield for comparative purposes. All results to date indicate that there is no need for restraining chains on the new designs. The spacer arrangement is definitely advantageous in preventing any bunching of baffles. The freedom of rotation on these new designs is considerably better than on the old Alter design.

Experiments conducted in the wind tunnel to determine the proper height of the baffle above the top of the gage revealed definite indications as to what height the top of the baffle should be. Table 3 gives data on the catch of sawdust snow in a Sacramento gage with various heights of the baffles above or below the orifice of the model for both an Alter shield and a modified Alter I shield. The results indicate that the top of the baffle should be placed about one-half inch above the top of the gage orifice on a prototype installation.

True-catch studies with the selector tube and the photographs against the gridwork revealed that the model Sacramento gage without a shield was catching about 27 pct of what it


Std. pipe cap
⅜" rod
Sash chain
Pipe support (3 reqd)
ALTER SHIELD
Inside view
½" tubing spacer
⅜" rod
MODIFIED ALTER SHIELD
Inside view
3"
1"
16"
1½"
20 ga. galv. iron
Cotter pin to hold sash chain
ALTER BAFFLE
3"
2"
18"
1½"
28 ga. galv. iron
MODIFIED ALTER I BAFFLE
3½"
⅛"
4½"
24"
2"
⅛"
MODIFIED ALTER II BAFFLE

Item	Alter	Mod. Alter I	Mod. Alter II
Number of baffles	24	33	27
Diameter of support ring	38	44	50

Fig. 10--Comparative dimensions and details for Alter windshield and modified Alter windshields

Table 2--Comparative catch of sawdust snow in different model precipitation gages with various types of shields

Gage type	Windshield type	Wt of catch (grams) for windspeeds of 15 mi/hr	Wt of catch (grams) for windspeeds of 8 mi/hr
Sacramento	None	5.3	. . . .
	Alter	8.4	10.4
	Mod. Alter I	12.3	10.0
	Mod. Alter II	7.9	8.5
Standpipe	None	6.6	. . . .
	Alter	10.8	10.7
	Mod. Alter I	12.2	12.4
	Mod. Alter II	10.1	12.2
Stevens Q-12	None	4.2	. . . .
	Alter	9.6	8.9
	Mod. Alter I	8.5	10.6
	Mod. Alter II	8.1	6.2
Standard	None	6.8	. . . .
	Alter	9.8	. . . .
	Mod. Alter I	10.3	. . . .
	Mod. Alter II	9.3	. . . .

Table 3--Comparative sawdust catch of shielded model Sacramento gage with various heights of the top of the baffles above or below the top of the gage

Baffle locations with respect to top of gage	Alter shield catch	Mod. Alter I shield catch
	gm	gm
1 inch below	8.5	9.2
1/2 inch below	8.8	9.3
Level with top	8.9	9.4
1/4 inch above	8.9	10.4
1/2 inch above	8.3	9.9
1 inch above	6.7	8.9

should have been catching. The same model gage with the best shield developed to date (modified Alter-I) showed a catch of about 60 pct of a theoretically true catch. All tests in this series were made with the fans operating at the fastest speed.

Particle velocities in the tunnel were found to be 16.5 mi/hr at the fastest speed of the fans. Consideration of the significant forces acting as the gravitational and inertia forces, indicates the corresponding particle velocity in the field would be 23.3 mi/hr.

Experiments in the field are much slower in producing significant results and as a consequence, that phase of the project is incomplete. However, some interesting trends are indicated in the results obtained up to this time. Table 4 is a summary of the weight measurements of precipitation catch obtained during the past four winter seasons at Mullan Pass. Note that some of the shields have been in operation on the gages for only one season (see Table 1). It is quite evident that shields play an important part in the amount of precipitation that is caught. Figure 11 gives a comparative picture of winter precipitation catch made by stick measurement in four of the Sacramento storage gages during the winter 1951-52 at Mullan Pass. It should be remembered that a single stick measurement of the contents of such a gage can be in error to a considerable extent by misreading a depth as much as 1/16 inch. However, the error is compensating, and the accumulative readings will give the desired accuracy. Note that the two new shield designs show a definite improvement and consistency in the amount of catch.

Table 4--Summary of winter precipitation records at Mullan Pass

Period	Precipitation in gage[a] 2	3	4	5	6	7
	inch	inch	inch	inch	inch	inch
9/17/48-4/15/49	38.4	47.4	33.9	45.3	. . .	. . .
9/16/49-4/7/50	57.3	Frozen	52.5	60.6	46.0	44.5
9/16/50-4/6/51	50.5	52.3	45.1	49.7	41.9	48.0
9/11/51-4/5/52	46.1	. . . . .	49.6	43.5	49.5	44.8

[a] See Table 1 for type of shield on the respective gages.

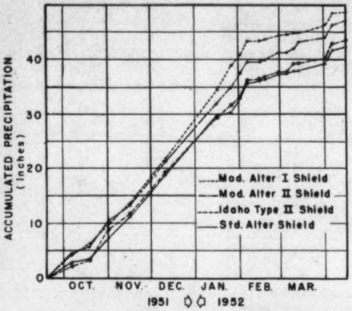


Fig. 11--Comparative winter precipitation catch in experimental storage gages at Mullan Pass, Idaho

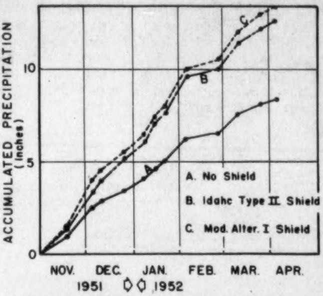


Fig. 12--Comparative winter precipitation catch in experimental U. S. Weather Bureau standard gages at Priest River Experimental Forest, Idaho

Figure 12 gives the comparative performance of three U. S. Weather Bureau standard rain gages located on Gisborne Mountain in the Priest River Experimental Forest. Here is shown the definite value of the windshield. Data on the gage with the modified Alter-I shield indicates the same positive results observed in the wind tunnel. Observations indicate that the Idaho Type II shield becomes frozen up much more quickly than the new shield and probably would cap over on occasions at Gisborne Mountain. Additional field testing is necessary to indicate whether the new shield design will prevent capping over due to formation of rime between the gage and shield.

Table 5--Snow tube measurements of precipitation compared to precipitation catch in experimental gages at Mullan Pass Experimental Plot

Period	Precipitation in gage				Snow tube
	2	4	6	7	
	inch	inch	inch	inch	inch
3/20/50-3/30/50	0.6	1.6	2.0	2.4	1.9
11/27/50-12/8/50	3.2	2.5	3.3	3.8	3.2
12/19/50-1/5/51	5.5	4.8	4.0	5.0	5.6
12/10/51-1/15/52	9.9	12.5	10.5	9.5	11.0

Snow-board measurements are not conclusive and need more careful observation than the program would permit. The results of a few measurements are indicated in Table 5. Notice some of the periods were long, and no record was kept of the drifting during the period. Constant attention at one of these boards for a very heavy storm might reveal a good standard with which to compare the gage measurements.

Conclusions

The performance of model precipitation gages under simplified and idealized conditions in a slow-speed wind tunnel has defined the air-flow behavior around the gages and gives definite information about the inconsistencies observed in records of snow catch in precipitation gages. The relative-catch studies of the amount of sawdust snow collected in a model gage have been an excellent guide for determining improvement in the design of given gage-and-shield combinations.

The limit of what is a theoretically true catch in a particular model gage has been defined in the wind tunnel through work with a sampling tube and a special photographic arrangement. From these various experiments, two windshields have been designed which promise to give better performance than shields in use at the present time. Both field and laboratory results appear to substantiate the value of the new designs. However, further field testing should be carried on to prove the performance of the shields. It is recommended that the various interested groups use these designs in independent tests.

Acknowledgments--Acknowledgment is here given for the assistance of the various federal agencies cooperating on this project. The Weather Bureau, Civil Aeronautics Administration, and the Forest Service have been very helpful in the field testing program. The Bureau of Reclamation and Corps of Engineers have both given much encouragement during the progress of the project. This project, Special Research Project 17, is made possible under the University of Idaho's Special Research Program and is under the direction of Allen S. Janssen, Director of the Engineering Experiment Station.

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Moscow, Idaho

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DISCUSSION

Walter T. Wilson (U. S. Weather Bureau, Washington, D. C.)--With notably little precedent Warnick has ingeniously produced some important and practical results in his work on performance of precipitation gages. In general he concludes that shielding of gages is necessary in windy storms and recommends that the Alter shield be modified by using a larger diameter supporting ring, more and longer baffles, and substituting for the restraining chain a set of annular spacers between the baffles around the supporting ring.

In the wind tunnel the air flow was fairly smooth, with no large eddies, and at prototype speeds of about 11 to 23 mi/hr. Sawdust snow entered the airstream horizontally. It would be interesting to note the results of sawdust falling into the air stream, perhaps in a manner more analogous to precipitating snow. As one might expect, Figure 2 shows differences between the smoke trajectory and the paths of sawdust particles which portray respectively the air stream and the movement of particles acted on more by gravity. If the average drift angle were found to be different for different wind speeds and for different positions along the trajectory of the sawdust, the optimum position of the shield might be indeterminate. The windshield in a natural exposure should have a shape and position which will give good average results for different wind speeds and degrees of turbulence.

Except for snow sometimes being stickier than sawdust the analogy seems good, at least for qualitative exploration. The density and size of snow flakes vary widely. In general, Warnick's determination of deficiencies in catch with high wind speeds agrees quantitatively with those of other investigators. However, in Table 2 the difference in wind speed shows less difference in catch than might be expected. An analysis of Tables 2 and 5 would probably disclose considerable variance, unexplained by either wind speed or type of gage.

As stated by Warnick, comparisons between gage catch and snowboard-and-tube data are inconclusive. In nature turbulence increases with height above the ground or snow surface, and gages with orifices high enough for deep snow can hardly fail to have deficient catch at times. It can well be imagined how much sawdust would remain on a snowboard in the wind tunnel.

Although Warnick may feel that he has reached a point of diminishing returns in his laboratory study of gage shields it is hoped that controlled experiments on gage performance will continue with the impetus he has given. Perhaps the effects of natural exposures of gages, and size and distance of obstructions, for example, can be evaluated. While Warnick's determination of true catch in the wind tunnel seems reasonable, prototype problems of turbulence, areal sampling and rugged terrain indicate possibly less need for approaching true-catch performance than for obtaining a consistent and reliable index relationship.

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ON TIDES IN ESTUARIES AND AROUND SMALL ISLANDS

Chia-Shun Yih

Abstract--Tides in estuaries and around small islands are studied in this paper. Under the assumption that the width and the mean depth of the estuary can be adequately expressed as power functions of the longitudinal distance from a certain point upstream, and that the depth of the ocean varies as a power function of the radial distance from the island, analytical solutions can be found by very simple transformations.

Tides in estuaries--The problem of determining the variation of the amplitude of tide in a gradually widening and deepening estuary while a periodic motion is maintained at sea is of some interest. With sufficient latitude one can assume that the width b and the average depth h of the estuary vary as certain arbitrary powers of x, which is measured along the estuary downstream from a certain point. Denoting by s, b_s, and h_s respectively the values of x, b, and h at the mouth of the estuary, one can write

$$b/b_s = (x/s)^m = \xi^m \tag{1}$$

$$h/h_s = (x/s)^n = \xi^n \tag{2}$$

where

$$\xi = x/s \tag{3}$$

The periodic motion maintained at the mouth of the estuary can be described by

$$\eta_s = C \cos(\sigma t + \epsilon) \tag{4}$$

where η is the deviation of the water surface from its equilibrium position and η_s is its value at $x = s$, t is the time, and C, σ, and ϵ are respectively the amplitude, frequency, and phase angle of the periodic motion. The differential equation for η at any point in the estuary is [LAMB, 1945, p. 274]

$$\partial^2\eta/\partial t^2 = (g/b)(\partial/\partial x)(h\, b\, \partial\eta/\partial x) \tag{5}$$

where g is the gravitational acceleration. In virtue of (1), (2), and (3), (5) can be written as

$$(s^2/g\, h_s)\, \partial^2\eta/\partial t^2 = \xi^{-m}(\partial/\partial\xi)(\xi^{m+n}\, \partial\eta/\partial\xi) \tag{6}$$

If one takes

$$\eta = C \cos(\sigma t + \epsilon)\, X(\xi) \tag{7}$$

then (6) becomes

$$\xi^{-m}(d/d\xi)(\xi^{m+n}\, dX/d\xi) + (s^2\sigma^2/g\, h_s)\, X = 0 \tag{8}$$

For convenience one writes

$$\lambda^{2-n} = s^2\sigma^2/g\, h_s \qquad \xi_1 = \lambda\xi \tag{9}$$

Then (8) becomes

$$(d/d\xi_1)(\xi_1^{m+n}\, dX/d\xi_1) + \xi_1^m X = 0 \tag{10}$$

To seek a solution of (10) in terms of familiar functions, one tries the transformations

$$X = \xi_1^p f(\zeta) \qquad \zeta = \xi_1^q \tag{11}$$

Then

$$dX/d\xi_1 = p\xi_1^{p-1} f(\zeta) + q\xi_1^{p+q-1} f'(\zeta) \quad \ldots\ldots\ldots\ldots\ldots \quad (12)$$

$$d^2X/d\xi_1^2 = p(p-1)\xi_1^{p-2} f(\zeta) + q(2p+q-1)\xi_1^{p+q-2} f'(\zeta) + q^2\xi_1^{p+2q-2} f''(\zeta) \quad \ldots \quad (13)$$

where the primes denote differentiation with respect to ζ. Substituting (11) to (13) into (10), one obtains

$$f'' + [(2p+m+n+q-1)/q\zeta]\, f' + \left[(\zeta^{\frac{-n-2q+2}{q}}/q^2) + p(p+m+n-1)/q^2\zeta^2\right] f = 0 \quad \ldots \quad (14)$$

Demanding

$$p = (1-m-n)/2 \qquad q = (2-n)/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

one obtains Bessel's differential equation

$$f'' + f'/\zeta + (1/q^2 - p^2/q^2\zeta^2)\, f = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

the solutions of which are $J_\nu(\zeta/q)$ and $J_{-\nu}(\zeta/q)$ where $\nu = |p/q|$. Of these two solutions, only one will give an $X(\xi_1)$ which is finite at $\xi_1 = 0$ together with $dX/d\xi_1$, unless ν is an integer, when they will coincide. One will assume $n \leq 1$, so that q is positive. Remembering $\zeta = \xi_1{}^q$, and that [WHITTAKER and WATSON, 1945, p. 359]

$$J_\nu(\zeta/q) = \zeta^\nu(a_o + a_2\zeta^2 + \ldots)$$

$$J_{-\nu}(\zeta/q) = \zeta^{-\nu}(b_o + b_2\zeta^2 + \ldots)$$

where a_o, a_2, b_o, b_2, etc., are numerical constants depending on ν, one easily sees that with p negative (so that $\nu q = -p$),

$$\xi_1^p J_\nu(\zeta/q) = \xi_1^{p+\nu q}(a_o + a_2\zeta^2 + \ldots) = a_o + a_2\zeta^2 + \ldots$$

$$\xi_1^p J_{-\nu}(\zeta/q) = \xi_1^{2p}(b_o + b_2\zeta^2 + \ldots)$$

$$(d/d\xi_1)\,[\xi_1^p J_\nu(\zeta/q)] = \xi_1^{q-1}(2a_2\zeta + 4a_4\zeta^3 + \ldots) = \xi_1^{1-n}(2a_2 + 4a_4\zeta^2 + \ldots)$$

$$(d/d\xi_1)\,[\xi_1^p J_{-\nu}(\zeta/q)] = 2p\,\xi_1^{2p-1}(b_o + b_2\zeta^2 + \ldots) + \xi_1^{2p+q-1}(2b_2\zeta + 4b_4\zeta^3 + \ldots)$$

Thus when p is negative, $\xi_1^p J_\nu(\zeta/q)$ and its derivative with respect to ξ_1 are finite at $\xi_1 = 0$ (recalling $n \leq 1$), whereas, with $2p - 1 = -(m+n)$, the quantity

$$(d/d\xi_1)\,[\xi_1^p J_{-\nu}(\zeta/q)]$$

is definitely infinite at $\xi_1 = 0$. Thus $A\xi_1^p J_\nu(\zeta/q)$ should be chosen to be the solution. Similarly, when p is positive, $B\xi_1^p J_{-\nu}(\zeta/q)$ should be used.

The constants A and B are determined from (4) (the boundary condition at $x = s$ where $\xi = 1$, $\xi_1 = \lambda$, $\zeta = \lambda^q$) to be

$$A = 1/\lambda^p J_\nu(\lambda^q/q) \qquad B = 1/\lambda^p J_{-\nu}(\lambda^q/q) \quad \ldots\ldots\ldots\ldots\ldots \quad (17)$$

Thus one concludes that, for negative p

$$\eta = CA(\lambda\xi)^p J_\nu(\zeta/q)\cos(\sigma t + \epsilon) \quad \ldots\ldots\ldots\ldots\ldots \quad (18)$$

and for positive p

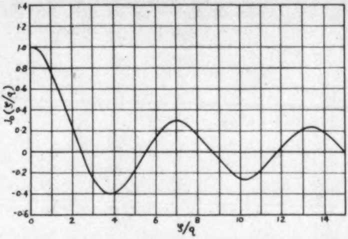
$$\eta = CB(\lambda\xi)^p J_{-\nu}(\zeta/q)\cos(\sigma t + \epsilon) \quad \ldots\ldots\ldots\ldots\ldots \quad (19)$$

where A and B are given by (17) and ζ is given by (9) and (11) to be $(\lambda\xi)^q$. When ν is an integer, the solutions given by (18) and (19) are identical.

As an example one takes the case m + n - 1, p =0. The solution is

$$\eta = CA\,J_o(\zeta/q)\cos(\sigma t + \epsilon)$$

In order to visualize the variation of the function J_0 (ζ/q), it is plotted in Figure 1 against ζ/q. It is seen that at certain points of the estuary the function is a maximum in absolute value, and these maximum values increase in the upstream direction, so that the tide is augmented in the neighborhood of these points. It is also seen that at certain other points of the estuary the function J_0 (ζ/q) is zero. These are the nodal points where the elevation of the water surface is not affected by the tide. Similar conclusions can be drawn for the cases in which p is not equal to zero.



The points at which the amplitude is a maximum are determined by

$$d\, J_0\,(\zeta/q)/d\,\zeta = 0$$

or [WHITTAKER and WATSON, 1945, p. 360, formula (B)]

$$J_1\,(\zeta/q) = 0$$

the roots of which are [JAHNKE and EMDE, 1945, p. 168]

$$\zeta_1/q = 0 \qquad \zeta_2/q = 3.832 \qquad \zeta_3/q = 7.016 \qquad \zeta_4/q = 10.173 \quad \ldots \qquad \ldots\ldots \quad (20)$$

the spacing of subsequent roots being approximately π. For cases in which p $\neq$ 0, the points at which the amplitude is a maximum can be similarly located.

The points of zero amplitude (the nodes) are determined by

$$J_0\,(\zeta/q) = 0$$

the roots of which are [JAHNKE and EMDE, p. 168]

$$\zeta_1/q = 2.405 \qquad \zeta_2/q = 5.520 \qquad \zeta_3/q = 8.624 \quad \ldots \qquad \ldots\ldots\ldots\ldots \quad (21)$$

the spacing of subsequent roots being approximately π. For cases in which p $\neq$ 0, the nodes can be similarly located. Of course, the actual number of nodes as well as that of maximum amplitudes is limited by the length of the estuary for a certain frequency and a certain h_s. If the value of λ calculated from (9) is too small, it may happen that there are no nodes at all, and that the only maximum amplitude occurs at ζ = 0 (or x = 0). This happens if the estuary is not extremely long. Thus for an ordinary estuary there is an augmentation of the amplitude of tide over its entire length.

Another point of interest is the phenomenon of resonance. There are many values of λ for which J_0 (λ^q/q) is zero. In fact, they are given by (21) on changing ζ to λ^q. For a given estuary there are many values of σ corresponding to these values of λ according to (9). These special values of σ will cause A to become infinite and can be called the natural or characteristic frequencies of the given channel. When the frequency at the sea comes near the natural frequencies of the channel, a state of resonance is approached. In such cases the given solution fails, and one is compelled to take friction into consideration. For an estuary of moderate length, σ is usually so small that even the first of these natural frequencies is not reached.

Tides around small islands--Supposing that r is measured radially from an island which is small compared with the wave length of the tide, and that the depth h of the sea is a power function of r

$$h/h_s = (r/s)^n \qquad (22)$$

where s is the value of r at which a periodic motion is maintained (at the open sea) and h_s is the value of h at r = s, one proposes to study the amplitude of tides around the island. Let the periodic motion at the open sea be represented by

$$\eta_s = C \cos(\sigma t + \epsilon)\, e^{i\mu\theta} \qquad (23)$$

where θ is the coordinate angle and the other quantities have the same meanings as before. The differential equation for η is [LAMB, 1945, p. 291]

$$\partial^2\eta/\partial t^2 = g\,(h\nabla^2\eta + (dh/dr)\,\partial\eta/\partial r) \qquad (24)$$

where

$$\nabla^2 \equiv \partial^2/\partial r^2 + (1/r)\partial/\partial r + (1/r^2)\partial^2/\partial\theta^2$$

and g is again the gravitational acceleration.

With $\rho = r/s$ one can write (24) as

$$(s^2/g\,h_s)\,\partial^2\eta/\partial t^2 = (\rho^n\,\nabla_\rho^2\,\eta + n\rho^{n-1}\,\partial\eta/\partial\rho) \qquad (25)$$

where

$$\nabla_\rho^2 \equiv \partial^2/\partial\rho^2 + (1/\rho)\,\partial/\partial\rho + (1/\rho^2)\,\partial^2/\partial\theta^2$$

Taking

$$\eta = C\cos(\sigma t + \epsilon)\,R(\rho)\,e^{i\mu\theta}$$

one has

$$\rho^n\,[R'' + (1/\rho)\,R' - (\mu^2/\rho^2)\,R] + n\rho^{n-1}\,R' + \lambda^{2-n}\,R = 0$$

where

$$\lambda^{2-n} = s^2\sigma^2/g\,h_s \qquad (26)$$

Writing ρ_1 for $\lambda\rho$, one has

$$d^2R/d\rho_1^2 + (2/\rho_1)\,dR/d\rho_1 - (\mu^2/\rho_1^2)\,R + (1/\rho_1^n)\,R = 0 \qquad (27)$$

To seek a solution in terms of familiar functions, one tries the transformations

$$R = \rho_1^{\,q}\,f(\zeta) \qquad \zeta = \rho_1^{\,q}$$

substitution of which into (27) yields, in a way similar to that of deriving (14)

$$d^2f/d\zeta^2 + [(2p + q + n)/q\zeta]\,df/d\zeta + \left\{[\zeta^{(-n+2-2q)/q}/q^2] - [\mu^2 - p(p+n)]/q^2\,\zeta^2\right\}f = 0$$

Demanding

$$p = -n/2 \qquad q = (2 - n)/2 \qquad (28)$$

one obtains the Bessel equation

$$d^2f/d\zeta^2 + (1/\zeta)\,df/d\zeta + [1/q^2 - (\mu^2 + n^2/4)/q^2\,\zeta^2]\,f = 0 \qquad (29)$$

the solutions of which are $J_\nu(\zeta/q)$ and $J_{-\nu}(\zeta/q)$ where

$$\nu = \sqrt{(\mu^2/q^2) + (n^2/4\,q^2)} \qquad (30)$$

It may be noted that since values of n greater than two are unlikely, q will be considered as positive. Since $p = -n/2$ is always negative, J_ν should always be chosen so that R will not have a pole at $\zeta = 0$. It is interesting to note that since $J_\nu(\zeta/q)$ varies as

$$\zeta^\nu = \rho_1^{(\mu^2+n^2/4)^{1/2}}$$

near the origin,

$$R = \rho_1^{\,p}\; J_\nu(\zeta/q) = \rho_1^{-n/2}\; J_\nu(\zeta/q)$$

varies there as

$$\rho_1^{(\mu^2+n^2/4)^{1/2}-n/2}$$

which vanishes at $\eta = 0$ for $\mu \neq 0$. Consequently, only the effect of the gravest mode corresponding to $\mu = 0$ is felt at the island.

In view of (23) (since $\rho_1 = \lambda\rho$ and $\rho = 1$ at $r = s$) the solution is thus

$$\eta = [C/J_\nu\ (\lambda^q/q)]\, \rho^{-n/2} J_\nu(\zeta/q) \cos(\sigma t + \epsilon)\, e^{i\mu\theta} \qquad \text{(31)}$$

This solution can be discussed in a way similar to that for the case of the estuary. It is topographically unlikely that any nodal circle exists for the low frequency of the ordinary tide. For the gravest mode ($\mu = 0$) usually there will be only one point of maximum amplitude, which is at the origin. Thus for this mode (which is the most likely to occur), the amplitude of tide increases with decreasing distance from the island.

For higher modes ($\mu = 1, 2, 3, \ldots$), there are nodal lines radiating from the island dividing the whole angle into equal segments.

It is obvious that (31) can be generalized to satisfy the following boundary condition at $r = s$

$$\eta_s = C \cos(\sigma t + \epsilon)\, F(\theta)$$

where $F(\theta)$ has a period 2π. All that is necessary is to expand $F(\theta)$ in a Fourier series, and to use as the solution the corresponding series consisting of terms like the one on the right side of (31).

Concluding remarks--Under the assumptions on which the calculations of this paper are based, it can be concluded from the foregoing that there is an augmentation of the amplitude of tide over certain portions of the estuary if it is extremely long, that this augmentation is over the entire length of the estuary if it is of ordinary length, that at the island only the effect of the gravest mode of the tide (which is the most likely to occur) is felt, and that for this mode the amplitude of tide generally increases with decreasing distance from the island.

It is worth noticing that if the periodic motion at the mouth of the estuary or in the open sea for the case of the island is described by a general periodic function of time, the corresponding problems can be solved by superposition and applying the Fourier series, utilizing the results obtained in the foregoing.

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FLOCCULENT STRUCTURE OF SEDIMENT SUSPENDED IN LAKE MEAD

Irving Sherman

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Abstract--More than half the weight and volume of sediment deposits in Lake Mead are fine-textured, being primarily silt and clay. These deposits have surprisingly low specific weights, much lower than can be accounted for by systems of particle packing or by particle size alone. The large volumes of deposits and slow rates of consolidation are of importance to those concerned with predictions of rates of sediment accumulation. This report interprets the low specific weight of deposited sediment in terms of behavior and structure in suspension prior to deposition.

In suspension, the sediment particles do not act as individuals, but, because of the salinity of the water, are grouped in floccules; these floccules are highly porous, their porosity being a function of component particle sizes. It is because of the porosity of the suspended floccules that the resulting deposits have such low specific weights.

The pores in the suspended floccules are so small, and their permeabilities so low, that water in them can be considered trapped there as an integral part of the floccules. The effective density of a suspended floccule is therefore not 2.65 gm/cm^3 but some lower figure which appears to approximate 1.4 gm/cm^3 for sediment with a median particle diameter of one micron.

Introduction--During 1948-49, at the request of the U. S. Bureau of Reclamation, a survey was made of the sediment accumulated in Lake Mead since the construction of Hoover Dam. The study was undertaken by the U. S. Geological Survey, with assistance by the Navy Department and other agencies.

The sedimentation study was less concerned with the mechanism of sediment transport than with the end results. Laboratory studies of sediment, to which the author was assigned, were confined almost entirely to deposited material. But the findings of that work are explainable only if there is considered the behavior of the sediments when suspended in the density currents which carried them through the lake. The paper presents some of the results of the investigation which show what the structure of suspended sediment must have been in order to produce these conditions.

Definitions--Listed below are definitions of terms as used in this report.

Adsorption (ionic)--The adherence of ions to the surfaces of colloidal particles by electrostatic attraction. Because most colloids carry negative charges, the adsorbed ions are usually positively charged (cations).

Air-dry moisture content--The amount of water which a material will retain adsorbed in equilibrium with air at room temperature, but which is driven off at 105° C.

Cation exchange--A chemical mass-action reaction in which cations adsorbed by colloids in contact with a solution go into solution and are replaced on the colloid surfaces by other cations from the solution.

Colloid--Matter divided into very small particles, with a resultant very high surface area per unit mass. Colloidal behavior is a function of the amount and nature of the surfaces. The upper limit of colloidal diameter is usually considered to be between two and five microns.

Consolidation--The one-dimensional compression of a system of granular solids by a steadily applied load, resulting in lowered porosity, increased specific weight, and loss of fluids.

Dispersion--An electrochemical phenomenon in which colloidal particles in suspension, in a state of relatively high electromotive potential, repel one another and thus behave independently.

Floccule--A group or cluster of individual sediment particles. produced by flocculation (coagulation).

Flocculation--An electrochemical action in which the electromotive potential of colloidal particles in suspension is overcome by the presence of electrolytes, allowing the particles to adhere to one another in groups.

Median diameter--The diameter of the individual particle at the center of mass of a group of particles arranged in order of size, so that exactly half of the mass of the group (whether arranged or not) occurs as smaller particles.

Median floccule--The floccule at the center of mass of a group of floccules arranged in order of settling velocities, so that exactly half of the mass of the solids in the group occurs as floccules with smaller settling velocities.

Sorting--The degree to which particles have been separated according to size.

Specific weight--The mass of solids per unit volume of a porous system.

Texture--The fineness or coarseness of a group of particles. It may be described by a name such as clay, expressed in terms of particle diameters, or indicated in terms of a dependent behavior, such as the tendency to adsorb moisture.

Three-phase system--A system containing solid, liquid, and gaseous phases.

Previous work--The modern theories of suspended sediment transport are based on the mechanics of turbulent flow of fluids. It has been shown that in open channel flow there is a marked distribution of sediment with depth, the higher concentration being at the bottom. A full discussion of the mechanics involved is given by VANONI [1946].

The movement of sediment through Lake Mead is effected by currents which move downstream along the former bed of the Colorado River. These currents usually have a different density than the main body of water, due to characteristics of salinity, temperature, and suspended sediment, and may sink to the bottom, float on top, or find an intermediate level. The currents maintain their identities for long distances through the lake. Most of the sediment thus transported gradually deposits within the reservoir, but a small percentage occasionally is found still suspended in the water discharged through the power house. The phenomenon was first reported by GROVER and HOWARD [1938]. Largely as a result of the interest aroused by that report, a tremendous volume of basic data has since been collected and published [NATIONAL RESEARCH COUNCIL, 1941, 1947].

The present report will be confined to a consideration only of the sediments themselves. Conclusions will be drawn as to the structure of sediment in suspension, but these will be deduced largely from the nature of the sediment deposits, which were extensively sampled during 1948-49. The deposits are characterized by a nearly horizontal upper surface and a high viscosity preventing appreciable flow. In the absence of a turbid current moving above, the upper surface is a sharp interface between sediment and clear water; the interface was often well preserved within a transparent modified Foerst sampling instrument lowered so as to bracket the interface.

By contrast with deposited material, suspended sediment simply muddies the suspending water without greatly increasing the viscosity. Currents of turbid water did not appear to have sharp upper boundaries; due to the fact that the sediment concentration decreases very rapidly with height above the bottom, the transition between turbid and clear water is very gradual. In the lower levels of the transporting currents sediment is passing from the suspended to the deposited state; sediment concentrations are high and current velocities are low.

Size analyses were made on all types of sediment, mostly on deposited material; corroboration from suspended sediment analyses showed that differences were of concentration and not of texture. This left no doubt as to the mode of transportation of the deposited material.

Where the Colorado River enters Lake Mead there is a deltaic deposit of relatively coarse material, dropped due to the initial decrease of current velocity. This report is concerned primarily with the silt and clay carried by currents of low velocity, often as far as the dam itself, and deposited downstream from the delta on the lake bottom.

Experimental size analyses of sediment--One of the important measures which may be used to describe a sediment is its texture or particle size distribution. Size analyses were made on nearly 300 samples of Lake Mead sediment. Because the sediments were very fine-textured, direct measurements of particle size such as by sieving were usually impractical. Instead, the settling velocities of the particles were measured by the pipette technique. Particle sizes were then computed from the settling velocities through the relationship expressed in Stoke's Law

$$w = 2\, g\, r^2\, (\rho_s - \rho_1)/9\eta \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where w is the constant limiting velocity reached by a settling particle after a short initial period of acceleration, g is the acceleration due to gravity, r is the radius of the spherical particle, ρ_s and ρ_1 are the densities of the particle and liquid respectively, and η is the viscosity of the liquid.

Implicit in (1) are a number of assumptions, most important of which is that the settling particles are spheres. As this is usually not true, sizes are expressed as "equivalent spherical diameters" which means that the particles described have settling velocities equal to those of spheres of the indicated diameters.

A full discussion of the assumptions implicit in Stoke's Law is given by KEEN [1931].

In the textural analysis of soils and similar granular materials there has always existed the problem of correlating laboratory results with behavior in nature. Measurements of individual particle sizes in the laboratory may give an erroneous picture of field behavior if in nature the particles act not individually but in groups. The problem is greatest in dealing with colloidal particles; because of their high surface area per unit mass, such particles are particularly liable to be affected by phenomena such as cation exchange. JOHNSON and LAWRENCE [1942] have shown that cation-exchange capacity is a direct function of surface area. In the presence of certain cations, or of high concentrations of any cations, the electromotive potential of colloidal particles is overcome and the particles adhere to one another in groups. In such cases the particles are said to be flocculated; when acting individually they are said to be dispersed. This is discussed by GRIPENBERG [1939].

A number of experimental size analyses were made on samples of deposited sediment in connection with selection of pretreatment and dispersion techniques. As a part of these, to investigate the relation between sediment behavior in the lake and after dispersion in the laboratory, these same samples were analyzed under simulated lake conditions. These involved no chemical dispersion, and used untreated lake water as received at the dam for the sedimentation fluid. Comparative data on three such samples from widely-separated parts of the lake are presented in Figure 1. It will be seen that there is a wide range of textures, as shown by analyses after dispersion; but the cumulative curves for settling velocities in lake water are all remarkably similar in shape.

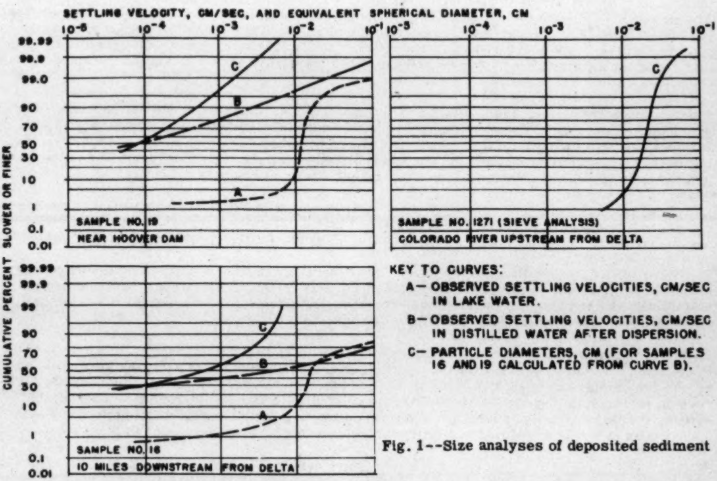

Fig. 1--Size analyses of deposited sediment

During the sediment sampling program some active density currents were found and sampled near the lake bottom, just above the sediment deposits, in a section extending 40 miles downstream from the delta. Size analyses were made on the sediment found suspended in these currents, analyses again being made under two sets of conditions for each sample. The analyses without chemical dispersion were made using as the sedimentation fluid the actual water in which the sediment was suspended when collected. The results of these analyses are presented in

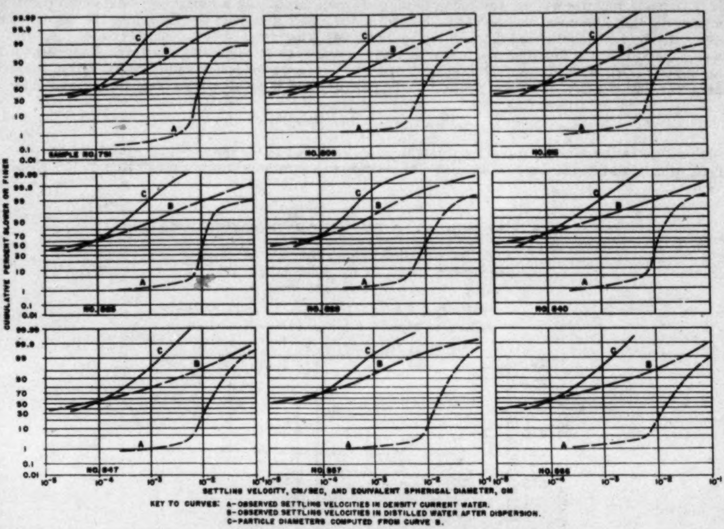

Fig. 2--Size analyses of suspended sediment

Figure 2. It will be seen that the textures of these samples from density currents are all very similar to each other and to the texture of the deposited sample from the downstream end of the lake shown in Figure 1, curve A. The settling velocities in natural lake water are also very similar to each other and to those of all samples in Figure 1 insofar as cumulative curve shape is concerned. (Detailed data on sample locations, depths, salinities, concentrations, and associated inflow and discharge conditions will be found in two associated reports [SHERMAN, 1950 and 1950a]. Details of the pipette analysis technique are given in the main report on the Lake Mead study [U. S. GEOLOGICAL SURVEY, in press].)

Almost no resemblance exists between the data for the two analysis treatments. Size analysis after maximum dispersion, useful for other purposes, does not give a true picture of sediment behavior in the lake. Because the discrepancies are so great, and because such a large percentage of the sediment is in the colloidal size range, it must be that in the lake the sediment is flocculated; individual particles or micelles are grouped or linked together in floccules. These floccules have greater diameters than the individual particles of which they are composed, and so their settling velocities are greater in accordance with the relationship of (1).

Specific weight of deposited sediment--The Bureau of Reclamation was primarily interested in knowing the rate of sediment deposition in the lake. The level of the upper sediment surface was measured by a hydrographic survey using sonic sounding equipment; comparison of this information with accurate contour maps made before the filling of the lake made possible the computation of sediment volume.

But it is not possible to use volume measurements alone to calculate the rate of sediment accumulation. The sediment deposit in the lake at any point in time will tend to occupy a constantly diminishing volume due to consolidation under the increasing load of new increments of sediment. For this reason it is desirable to have data on specific weight of the deposits and consolidation rates, and so laboratory measurements of specific weight were made and weights of sediment calculated.

Deposit specific weight was found to be quite variable, being a function of horizontal position within the lake, texture, and degree of consolidation. Samples from the bottom of the deposit were naturally more consolidated than overlying samples. The typical relationship between specific weight, texture, and vertical position is shown for one core in Figure 3. Texture is expressed in terms of the air-dry moisture content; this single-number expression is a function of the surface area per unit mass of the solid portion of the sample, and was calculated from the expression

$$P_{wa} = (m_a - m_o)\ 100/m_o \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where P_{wa} is the air-dry moisture content in percent, m_a is the mass of the sample in equilibrium with air at room temperature, and m_o is the mass of the sample after drying at 105°C for 24 hours.

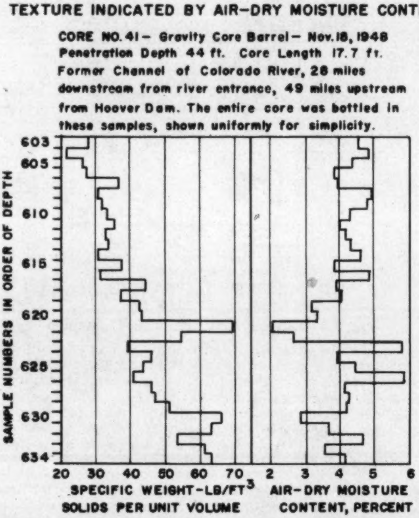

Fig. 3--Texture and specific weight relationships for one core

As the air-dry moisture content is quickly and easily measured, it was measured for all sediment samples; actual size analyses could be made for only about 20 pct of the samples collected. The inverse relationship between specific weight and air-dry moisture content, as shown in Figure 3, indicates that the latter is a good indicator of texture and permeability.

Investigation showed that the initial specific weight of newly-deposited sediment appears to be largely a function of texture. The relationship is shown in Figure 4. There are two sources of error in the data represented by Figure 4. Firstly, it is difficult to determine the exact boundary between concentration by sedimentation of independently-moving particles or floccules, and concentration by consolidation of a semi-solid deposit. The specific weights shown are those of the uppermost samples from the deposit at various stations, but it cannot be said that no consolidation whatsoever has taken place within them. The trend lines shown are the author's attempt to indicate the probable initial states of the deposits after sedimentation but before consolidation; for purposes of simplification it is assumed in this report that the trend line shown in Figure 4a is definitive.

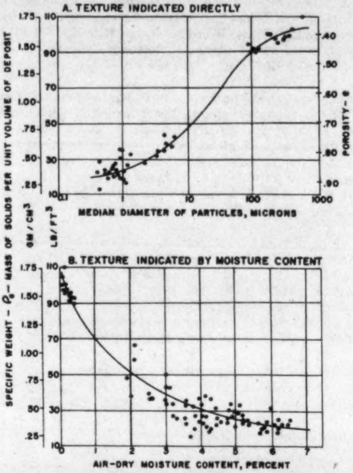

Fig. 4--Texture, specific weight and porosity relationships for unconsolidated sediments

The other source of error lies in the technique of measuring the air-dry moisture content. This determination should be made in a controlled atmosphere with constant temperature and humidity. No such atmosphere being available, the determinations had to be made in the open air of the laboratory and were affected by variations in that air.

The plotted points in Figure 4 fall in two clusters with large gaps between because most of the material carried into Lake Mead is extremely fine-textured, and is represented by the larger cluster of points. The smaller cluster represents coarser sand samples taken from the Lower Granite Gorge, upstream from the delta front, where river conditions now obtain because of aggradation. The transition between the two types of material occurs within a distance of only one and one-half miles just below the entrance of the river into the lake, as compared with the 77-mile distance from that point to the dam.

Theory of sediment structure--It will be seen from Figure 4 that most of the deposits have very low initial specific weights. The porosities may be calculated from the specific weights, the equation for the transformation being

$$e = 1 - \rho_a/\rho_s \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where e is the porosity, ρ_a is the specific weight (solids only per unit volume) of the deposit, and ρ_s is the density of the sediment (solid) itself. Porosity values from (3) are shown for the unconsolidated deposits by the ordinate scale at the right of Figure 4a. In that transformation the values of ρ_s used were calculated from the expression

$$\rho_s = 2.72 - (.025)(\log_{10} M) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where M is the median diameter of the sample particles in microns. Eq. (4) is the rectilinear least-squares line of regression established empirically in the laboratory for Lake Mead sediments.

GRATON and FRASER [1935] have shown that in an assemblage of uniform spheres, chance or random packing usually produces a porosity approximating 0.40. If uniform packing obtains, the maximum possible porosity is 0.4764, which occurs when the spheres are arranged in a cubic lattice; this lattice is unstable and tends to rotate so as to produce a closer packing. And in the assemblage of spheres of varying sizes, **WESTMAN** and **HUGILL** [1930] have shown that porosities tend to be reduced below those of assemblages of uniform spheres because the smaller spheres tend to occupy the pores between the larger spheres.

FRASER [1935] has shown that any increase in particle angularity away from sphericity tends to increase the porosity of the deposit formed. Using crushed mica, Fraser obtained an initial porosity of 0.9353. Although most of the individual particles of Lake Mead sediment are probably not spherical, we cannot attribute the high initial porosities shown in Figure 4a to particle shape alone. Firstly, the individual particles are not all as extremely planar as mica; they cover a wide range of shapes. Secondly, when samples of sediment were chemically dispersed for size analysis, the resulting deposit at the bottom of the sedimentation cylinder always had a lower porosity than deposits of like-textured fresh sediment in the lake.

The author measured the porosity of such a deposit from dispersed sediment. The sample had a median particle diameter of 1.53 microns, with a size distribution curve very similar in shape to that of Sample 19 (Fig. 1). Figure 4a indicates an initial porosity in the lake for such deposited sediment of approximately 0.84. The sample was dispersed by adding sodium hexametaphosphate (our standard dispersing agent) and shaking in a reciprocating shaker for a few hours. It was then made up into a two per cent suspension in distilled water and allowed to settle. The resulting deposit had a porosity of approximately 0.65.

Thirdly, we know that in the lake the particles are grouped in floccules, so it is with floccule shape rather than particle shape that we are concerned. The formation of floccules being dependent on the spherical radius of attraction of the particles [**KEEN**, 1931], it seems logical that the floccules will tend to be roughly spherical; microscopic examination by the author of a deposit of sediment floccules indicates that this is so.

The porosity of unconsolidated Lake Mead deposits is much greater than would be expected between roughly spherical floccules. The maximum porosity explainable by a system of packing for spherical particles is 0.4764, but the total initial porosity for a deposit with a median particle diameter of one micron is approximately 0.85 (from Fig. 4a). There is a difference in porosity for such material of at least 0.37; the only possible place where this additional porosity can exist is within the floccules themselves. The floccules thus are not solid but porous, containing considerable volumes of voids. For the floccules forming a deposit with a median particle diameter of one micron, the solids apparently occupy less than a third of the floccule volume.

Movement of water through sediment floccules--Consider a floccule of colloidal particles in aqueous suspension. Being in a gravitational force field, the floccule will tend to settle through the water and will thus have a velocity with respect to the water. We can simplify the problem somewhat by considering instead the velocity of the water with respect to the floccule; this will of course be equal and opposite.

If the velocity of the water with respect to the floccule is w, the water will tend to flow through the pores of the floccule with an average velocity $\bar{v}$, defined for any one pore as

$$\bar{v} = Q/\pi r^2 \quad \text{.......................} \quad (5)$$

where Q is the rate of flow in cm^3/sec and r is the pore radius in centimeters. Each pore may be considered as similar in many ways to a simple cylindrical capillary tube. The flow of fluids through such tubes was investigated by Poiseuille, who found that for laminar flow, where Q and r are as in (5)

$$Q = (\Delta p)(\pi r^4)/8 L \eta \quad \text{....................} \quad (6)$$

Δp is the pressure difference between the ends of the tube in $dynes/cm^2$, L is the tube length in cm, and η is the fluid viscosity in poises or $dyne\text{-}sec/cm^2$.

Substituting from (5) into (6) gives

$$\bar{v} = \Delta p \, r^2/8 L \eta \qquad \text{or} \qquad \Delta p = 8 \bar{v} L \eta / r^2 \quad \text{.............} \quad (7)$$

Poiseuille found that (6) and (7) did not hold if L/r was less than approximately 14. Working independently, Hagen developed an expression which held for all values of L/r, and which **TIETJENS** [1934] gives in corrected form as

$$\Delta p = 8\,\bar{v}\,L\,\eta/r^2 + 2\,\bar{v}^2\,\rho_1/2 \qquad (8)$$

where ρ_1 is the liquid density in gm/cm^3.

Of course, the pores in a floccule are not uniform cylinders, so it is necessary to substitute for r an effective radius or hydraulic radius, r_h. This is usually defined as the ratio between cross-sectional area A and wetted perimeter; for a uniform cylindrical tube flowing full, the wetted perimeter is the circumference c. So

$$r_h = A/c = \pi r^2/2\pi\, r = r/2 \qquad \text{or} \qquad r = 2\,r_h \qquad (9)$$

FAIR and HATCH [1933] have expressed the hydraulic radius of a network of pores in terms of more directly measurable quantities by introducing the length L of the network. Introducing L into equation (9) produces

$$r_h = AL/cL \qquad (10)$$

for which it is evident that AL is the volume of the tube and cL the wetted surface area. By analogy in a unit volume of a porous system AL is the porosity e, and cL is the surface area of the solid particles S. For such a system, then

$$r_h = e/S \qquad \text{or} \qquad r = 2e/S \qquad (11)$$

which, substituted in (8) gives

$$\Delta p = 2\,\bar{v}\,L\,\eta\,S^2/4\,e^2 + 2\,\bar{v}^2\,\rho_1/2 \qquad (12)$$

Hagen and Poiseuille worked with Δp as a static head. In the case of a floccule settling through a fluid only a velocity head exists. Several approaches to this problem are possible; one which yields much useful information involves calculating the required magnitude of Δp for certain flow conditions. A typical example follows.

Consider the median floccule of Sample 19 (Fig. 1). This floccule has a settling velocity of approximately 1.2×10^{-2} cm/sec. What must the magnitude of Δp be to create a mean flow velocity $\bar{v}$ of 1.2×10^{-6} cm/sec through the floccule pores? The median diameter of the particles in Sample 19 is very nearly one micron, so according to Figure 4 the porosity of the resulting unconsolidated deposit is approximately 0.85. If we accept the Graton and Fraser value of 0.40 for the porosity around the settled floccules, the porosity within the floccules is 0.45; or the volume of floccules is 0.60, of which 75 pct is pores and 25 pct solids.

The surface area of the solids is dependent on particle shape; assuming spherical shapes will result in the minimum computed value of Δp. Assuming the particles to be uniform in size will have the same effect. This makes S, the surface area of particles per unit floccule volume, then

S = (number of particles) (area of one particle)

= (total volume of particles) (area of one particle)/(volume of one particle)

$$= [(1 - e)\,\pi\, d^2]/(\pi\, d^3/6) = 6\,(1 - e)/d \qquad (13)$$

where d is the particle diameter in cm.

For one cm^3 of floccules with uniform particle diameters of one micron, where e is 0.75, S is 1.5×10^4 cm^2. The ratio e/S will be constant for such floccules, independent of individual floccule volume.

From (1), a solid with a density of 2.72 gm/cm^3 and a settling velocity of 1.2×10^{-2} cm/sec has an equivalent spherical diameter of 11.3 microns and thus a volume of 0.59×10^{-9} cm^3. This is then the minimum volume of solids in the median floccule. But as 75 pct of the floccule volume is pore space, the total floccule volume is 2.36×10^{-9} cm^3, and the floccule diameter is approximately 16.5 microns. The average length of pore $\bar{L}$ is the volume divided by the cross-sectional area, $(1/6\,\pi D^3)/(1/4\,\pi D^2)$, or 2D/3. So $\bar{L}$ is 11 microns. For water ρ_1 is 1.0 (approximately) and η is 0.01 (approximately). Substituting these values in (12) we find that Δp for these conditions is 26.5×10^{-4} gm/cm^2, which is a minimum limiting value because of the manner in which the assumptions were made.

The meaning of this may be more forcibly stated by pointing out that in order to create a flow velocity $\overline{v}$ which is only 10^{-4} times the settling velocity, the hydraulic gradient $\Delta p/L$ must be not less than 2.4 gm/cm^2/cm, or 2.4 times the gradient producible by gravity. A mechanism for creating such a pressure differential in a submerged floccule has not yet been proposed, and so even 10^{-4} is too large for the ratio of $\overline{v}/w$.

We may now check the applicability of (8) by computing that criterion of laminar versus turbulent flow, the Reynolds Number, R

$$R = \overline{v}\, r\, \rho_1/\eta = 2\, \overline{v}\, e\, \rho_1/\eta S \quad \text{.................... (14)}$$

For the assumed conditions R is

$$(2)\ (1.2 \times 10^{-6})\ (0.75)\ (1)/(0.01)\ (1.5 \times 10^4) = 1.2 \times 10^{-8}$$

Inasmuch as it is considered that laminar flow exists when R is less than approximately 1000 [TIETJENS, 1934], it is evident that the flow through the floccule pores is laminar and so (8) does apply.

The magnitude of $\overline{v}$ is so small that it may be considered to be negligible, that is, zero. Any water in the pores of a floccule may be considered to be trapped there, to move with the floccule, and to be an integral part of it.

Density of floccules in suspension--Because the water within the floccule pores is trapped there and must be considered as part of the floccule, it must be taken into account when the density of floccules is calculated. The following computations all assume that only solid and liquid phases are present; measurements made on the Lake Mead sediments showed this assumption to be justified as a working approximation. Deposits never contained more than two per cent of gas by volume. Then

$$\rho_f = (m_s + m_l)/(V_s + V_l) \quad \text{.................. (15)}$$

where ρ_f is the density of the floccule including its trapped water, m_s and V_s are the mass and volume, respectively, of the solids, and m_l and V_l are the mass and volume, respectively, of the liquids in the floccule.

An average value of ρ_f can be calculated from unconsolidated deposits if the arrangement of floccules within the deposits is known. In addition to their internal porosity, there will be a volume of pores around and between the floccules when they have settled to form a deposit. This porosity between floccules will henceforth be referred to as "deposit porosity."

Eq. (15) can be transformed to

$$\rho_f = [m_s + \rho_l(V_t - m_s/\rho_s - e_d)]/V_t\,(1 - e_d) \quad \text{............ (16)}$$

where e_d is the deposit porosity defined above, V_t is the total volume of deposit, and the other terms are as previously given. For a unit volume of deposit $V_t = 1$, $m_s = \rho_a$ of (3), and the expression becomes

$$\rho_f = [\rho_a + \rho_l\,(1 - \rho_a/\rho_s - e_d)]/(1 - e_d) \quad \text{............. (17)}$$

or, if ρ_l is taken as 1.0 for water (cgs units) and substituting from (3)

$$\rho_f = [\rho_a + (e_t - e_d)]/(1 - e_d) \quad \text{................. (17a)}$$

where e_t is the total porosity of the deposit. ρ_f as here calculated will be a mean value for all floccules present.

The magnitude of the deposit porosity e_d is still in need of investigation but let us assume that it has a value of 0.40 as found by GRATON and FRASER [1935] for random packing of rigid uniform spheres. It is then possible to apply (17a) and determine ρ_f for the various sediment deposits. Such values are shown for unconsolidated deposits in Figure 5; each point on the trend line shown has been obtained from the (texturally) equivalent point in Figure 4a.

By definition the unconsolidated deposit is assumed to consist of floccules which have not yet been deformed or lost any trapped water. So it can be assumed that the curve in Figure 5 represents not only floccules after deposition and before consolidation, but also the floccules in suspension before deposition. Then the average porosities of these floccules in suspension can be calculated from the unconsolidated deposit porosity using the expression

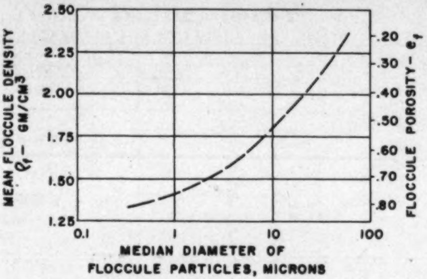

Fig. 5--Texture, density and porosity for suspended sediment

$$e_f = (e_t - e_d)/(1 - e_d) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

where e_f is the average porosity within the floccules expressed in terms of floccule volume, e_t is the total porosity of the resultant deposit, and e_d is the deposit porosity around the floccules. The values of e_f for Lake Mead sediments are shown by the ordinate scale at the right of Figure 5. It will be seen that e_f appears to be of considerable magnitude for sediments whose particles are mostly in the colloidal size range, and decreases sharply as the median diameter increases through the silt sizes.

The pipette analyses in the Lake Mead laboratory involved measurements at certain predetermined settling velocities. Figure 6 shows for each of these velocities the relation between floccule diameter and ρ_f, calculated from (1). If, for example, it is found that at any given velocity the sediment is settling in floccules for which $\rho_f = 1.4$ rather than as individual particles for which $\rho_s = 2.65$, the diameter of the floccule must be approximately double the diameter of an individual particle with the same settling velocity.

Inasmuch as the values of ρ_f obtained from (17) are mean values covering all of the floccules in a deposit, they cannot be applied as in Figure 6 to individual floccules. Because of the correlation between texture and floccule density shown in Figure 5 it is necessary to define the particle-size distribution within an individual floccule in order to calculate the density of that floccule in suspension. This will be treated in the following section.

Particle-size distribution within floccules--Let us investigate the distribution of particle sizes within an individual floccule. Considering the data of Sample 19 (Fig. 1) it is seen that the median diameter is 0.91 microns. Assume for a moment that the median floccule is representative of the entire sample and has the same particle size distribution. Then, from Figure 5, the density of this floccule is 1.405 and the porosity is 0.77, so the sediment volume is 23 pct of the total. Figure 1 gives the settling velocity of the median floccule as 1.2×10^{-2} cm/sec; interpolation in Figure 6 gives the diameter of this floccule as 23 microns. If the floccule is spherical, its volume is 6.38×10^{-9} cm^3.

On analysis of the cumulative percentage curve for sample 19 in Figure 1 we find:
0.8 pct of the sample occurs as particles larger than 32 microns,
1.2 pct of the sample occurs as particles between 16 and 32 microns,
3.5 pct of the sample occurs as particles between 8 and 16 microns,
10.5 pct of the sample occurs as particles between 4 and 8 microns,
16.0 pct of the sample occurs as particles between 2 and 4 microns, and
16.2 pct of the sample occurs as particles between 1 and 2 microns.

Inasmuch as a floccule cannot contain any particles larger than itself, it is obvious that the particle-size distribution within the median floccule cannot possibly duplicate this. The entire volume of sediment in the median floccule would be accounted for by just one particle 14.1 microns in diameter, and this would not be a floccule by itself.

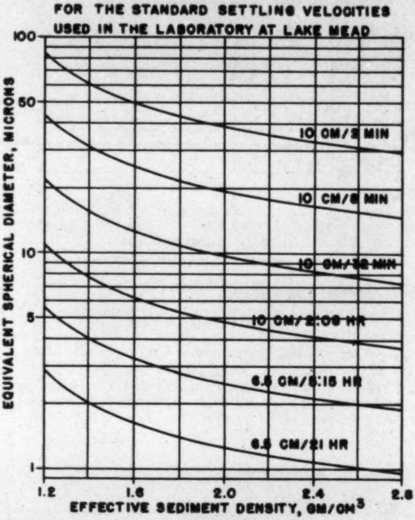

Fig. 6--Density-diameter relationships for sediment in suspension

Further, upon examination of the curves in Figures 1 and 2 it is seen that at settling velocities greater than approximately 5×10^{-2} cm/sec the curves for dispersed particles and the curves for floccules are separated by less than one per cent. This can only mean that most particles with such velocities act independently and do not form or enter floccules even without dispersion. Such particles will then settle according to their true densities of approximately 2.65 gm/cm^3; Figure 6 shows their diameters to be approximately 24 microns or greater.

It is to be expected that such coarse particles will tend to act independently. Compared with colloidal particles their surface area per unit mass is very low and surface effects would play a relatively minor part in determining their behavior. But if such particles act independently they will not be found in floccules. So the working assumption made in the first paragraph of this section, that the median floccule has the same particle size distribution as the entire sample, cannot possibly be true.

Then it must follow that:

(1) No floccule can have a particle-size distribution identical to that of the entire sample.

(2) The particles within any individual floccule have been more closely sorted than the particles in the entire sample; the range of particle sizes within any one floccule will necessarily be smaller than the range for the entire sample.

(3) Coarser particles can form only larger floccules; because deposits of coarser particles are relatively denser, it must follow that larger floccules will be denser floccules. Conversely finer particles will form primarily smaller floccules which will be more buoyant floccules.

(4) The median floccule may have the same median particle diameter as the entire sample, but at present it is not known if this so. Until the median diameter of particles in the individual floccule is known we cannot calculate individual floccule density or diameter by these methods.

It will now be shown that each floccule must contain particles of various sizes, and cannot be made up of particles of one size only. Figures 1 and 2 show that the range of settling velocities which includes 90 pct of the weight of floccules is comparatively narrow. This indicates a narrow range of current velocities and sediment transfer coefficients at any one location. So if the particles had been dispersed in the lake, it would be expected that the range of particle sizes in any one sample would be correspondingly narrow. Such close sorting is actually found in the river deposits upstream from the delta front; current velocities in this section are ordinarily so high that only coarse material not subject to flocculation is deposited. The size analysis for such material is shown in Figure 1, Sample 1271. It will be seen that the shape of the cumulative size distribution curve for this sample is remarkably similar to the cumulative floccule settling velocity curves of Figure 2.

If individual floccules consisted of particles of uniform size, the cumulative size analysis curve for particles in a sample would be very similar in shape to the cumulative settling velocity curve for the floccules in that sample. But this is certainly not so, and so each floccule must contain a range of particle sizes.

So it must be that the poor sorting of samples in the colloidal size ranges is not due to conditions of current velocity but to the fact that the colloidal particles are grouped in floccules each of which includes particles of many different sizes. Once the particles are so grouped they cannot be sorted to any great extent by differentials of current velocity.

In considering the porosity and density of an individual floccule in suspension, it should be remembered that the narrower range of particle sizes within a floccule as compared with the wider range in an entire sample may have considerable significance. As cited above, WESTMAN and HUGILL [1930] showed that an assemblage of uniform spheres has a higher porosity than an assemblage of spheres of many sizes (a fact long recognized in concrete design); so a floccule with a comparatively narrow range of particle sizes should have a different porosity and density than a sample with a wide range of particle sizes would indicate, even though both might have the same median diameter particle. Presumably the floccule would have a higher porosity and lower density than would be indicated by Figure 5, but the exact relationship remains to be established.

Conclusions--The following conclusions are drawn.

(1) The deposits of fine-textured sediment in Lake Mead have extremely high porosities and low specific weights. These characteristics result from the structure of the sediment in suspension which settled out to form the deposits.

(2) In suspension the finer particles do not behave independently but are grouped in floccules. These floccules are highly porous, and it is this which accounts for the very high porosity of the resulting deposits.

(3) The floccule structure is at least partly a function of salinity, and can be destroyed or reconstituted by changes in the salinity such as are made in dispersion pretreatments. This suggests that any prediction of the specific weight of sediment deposits in reservoirs should take the salinity of the water into consideration.

(4) Particles larger than approximately 24 microns in diameter do not enter into floccule formation regardless of salinity, but act independently in suspension.

(5) The pores within floccules are so small that the permeabilities are negligible. Water within the pores of a suspended floccule may be considered trapped there and an integral part of the floccule.

(6) Because of trapped water within, floccule density will not be 2.65 gm/cm^3 but some lower value, which averages 1.4 gm/cm^3 for the floccules of a sample with a median particle diameter of one micron.

(7) Most samples downstream from the delta at the head of the lake, whether suspended or deposited, show poor sorting of particle sizes but a narrow range of floccule settling velocities. It must therefore be that each floccule included a range of particle sizes and thus prevented their being sorted by differentials of current velocity.

(8) The particle-size distribution within any individual floccule will have a greater degree of sorting than that of the entire sample of which the floccule may be a part.

(9) The porosity within a floccule will be a function of component particle size. Relatively coarse particles (but smaller than 24 microns) form floccules with lower porosities than those composed of colloidal particles.

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TRAP EFFICIENCY OF RESERVOIRS

Gunnar M. Brune

Abstract--Forty-four records of reservoir trap efficiency and the factors affecting trap efficiency are analyzed. The capacity-inflow (C/I) ratio is found to offer a much closer correlation with trap efficiency than the capacity-watershed (C/W) ratio heretofore widely used. It appears likely from the cases studied that accurate timing of venting or sluicing operations to intercept gravity underflows can treble or quadruple the amount of sediment discharged from a reservoir. Desilting basins, because of their shape and method of operation, may have trap efficiencies above 90 pct even with very low C/I ratios.

Semi-dry reservoirs with high C/I ratios, like John Martin Reservoir, may have trap efficiencies as low as 60 pct. Truly "dry" reservoirs, such as those in the Miami Conservancy District, probably have trap efficiencies in the 10 to 40 pct range, depending upon C/I ratio.

Introduction

The trap efficiency of a reservoir depends upon a number of factors. Among these are the ratio between storage capacity and inflow, age of the reservoir, shape of the reservoir basin, the type of outlets and method of operation, the grade-size characteristics of the sediment, and the behavior of the finer sediment fractions under various conditions. A number of attempts have been made to correlate trap efficiency with one or more of these factors.

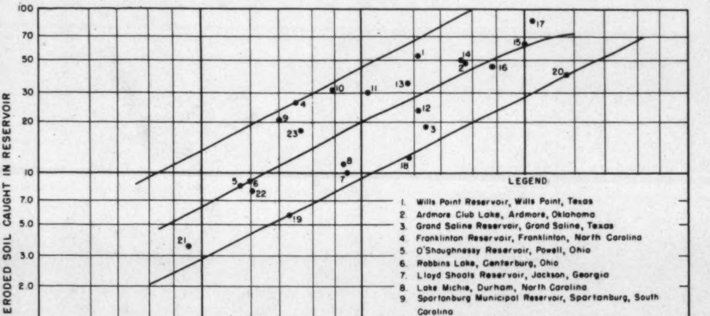

Fig. 1--Percentage of eroded soil caught in reservoir as related to capacity per square mile of drainage area

One of the earlier studies of trap efficiency was made by BRUNE and ALLEN [1941], who developed a curve relating percentage of eroded soil caught in the reservoir with capacity per square mile of drainage area. This curve is shown in Figure 1. The rate of soil erosion in each watershed was estimated by surveys and compared with the rate of reservoir sedimentation. The trap-efficiency values given in this curve, however, are necessarily low, because they are based upon rates of erosion rather than rates of sediment production to the reservoir. As GLYMPH [1951] has pointed out, the rate of sediment production is usually lower than the rate of erosion, and increasingly so the larger the drainage area because of the deposition of some of the eroded material on flood plains and in stream channels.

In the past, the ratio between storage capacity and inflow has been expressed in a general way by the capacity-watershed (C/W) ratio. BROWN [1943] first developed a curve relating C/W ratio and true trap efficiency. This curve, shown in Figure 2, with some additional records, is represented by

$$C_T = 100\,[1 - 1/(1 + 0.1\ C/W)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where C_T = reservoir trap efficiency, per cent, and C/W = reservoir capacity, acre feet per square mile of drainage area. There is considerable spread in the points.

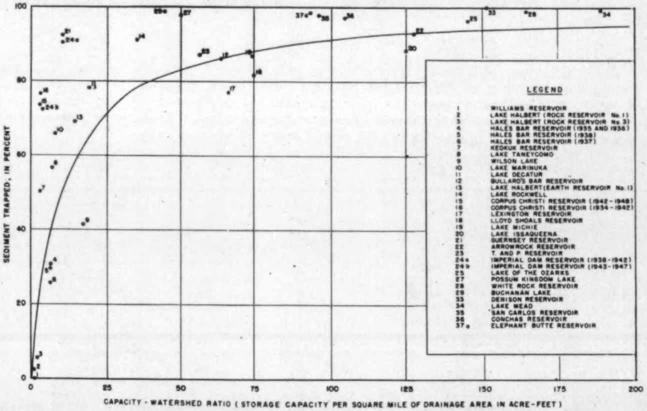

Fig. 2--Trap efficiency as related to capacity-watershed ratio

One difficulty with plotting this type of data on graph paper is that in the low C/W ratio range (under ten acre feet per square mile, the points are crowded, while in the high range (over 250) they cannot be plotted at all without greatly extending the abscissa. The points also follow a curved line, which approaches a trap efficiency of 100 pct asymptotically as the C/W ratio increases. In order to simplify plotting and to obtain a straighter line, the same data have been plotted on semi-log paper in Figure 3. The plotting of points is simplified, and the hyperbolic relationship results in a plot which is closer to a straight line on semi-log paper.

The main reason for the spread of points in this curve is that reservoirs having the same C/W ratio may have very different capacity-inflow ratios, as previously stated by GOTTSCHALK [1948]:

> A reservoir in an arid or semi-arid region may have a low capacity-watershed ratio yet not receive enough inflow in any one year to cause water to be discharged over the spillway. In contrast, the volume of mean annual flow from a watershed of equal size in a humid area may be equivalent to 25 times that of a reservoir having the same capacity-watershed ratio. In the drier region 100 pct of the incoming sediment load is trapped, whereas in the humid area possibly only 70 pct is trapped.

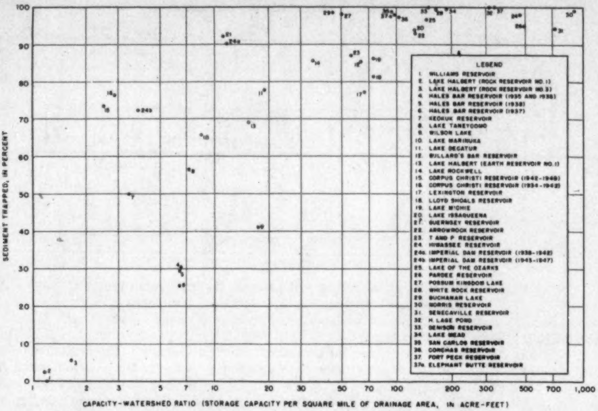

Fig. 3--Trap efficiency as related to capacity-watershed ratio

HAZEN [1914] first introduced the storage, or capacity-inflow, ratio in 1914. He used it for determining reservoir storage requirements, however, and not as an index of sediment trap efficiency.

For individual reservoirs, curves can be drawn correlating trap efficiency with detention time in days. BORLAND [1951] has prepared such a curve for Imperial Dam Reservoir (Fig. 4). Such curves are quite satisfactory for specific reservoirs, since other factors such as sediment characteristics, shape of the reservoir, and method of operation tend to remain constant.

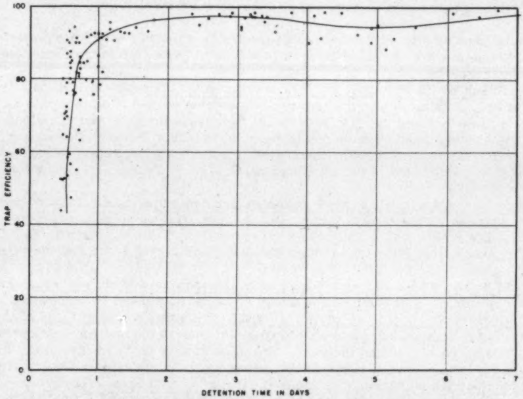

Fig. 4--Trap efficiency as related to detention time,
Imperial Dam Reservoir, Yuma, Arizona

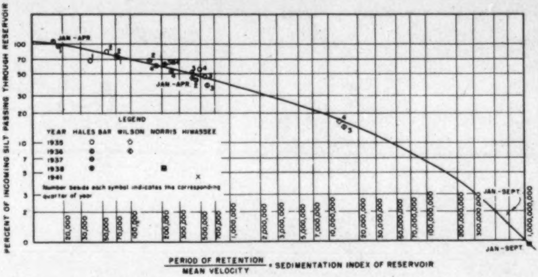

Fig. 5--Per cent of incoming silt passing through reservoir as related to sedimentation index, TVA reservoirs

CHURCHILL [1948] has taken into account both detention time and velocity of flow through the reservoir. He has developed a "sedimentation index" which represents the period of retention divided by mean velocity. His curve, relating trap efficiency to the sedimentation index for several TVA reservoirs, is shown in Figure 5. While this curve is very satisfactory where the data are available, such information as period of retention and mean velocity are not readily available for most reservoirs.

Methods used in the present study

For the present study a thorough search was made for all reliable records of reservoir trap efficiency, canvassing all of the agencies of the Federal Inter-Agency River Basin Committee known to be interested in this subject. Information was also gathered on capacity, annual inflow, shape of reservoir basin, type of outlets and method of operation, observed gravity underflows or "density" currents, and any other pertinent data.

Some 44 records were gathered, and are summarized in Table 1. Of these, 40 are for normal ponded reservoirs, with information on the effect of sluicing and venting operations on three. Two records are for desilting basins, and two for semi-dry reservoirs.

It is possible to study trap efficiency of reservoirs by a number of different methods, and it was necessary to use practically all of them in this study. The methods used are described briefly in the following paragraphs.

(1) Reservoir surveys with suspended-load measurements downstream--In this type of study the annual sediment accumulation in the reservoir is measured, and sediment passing over the dam or through outlets is sampled. The sum of the two yields the total sediment load of the stream. This method was used on most of the records, including Senecaville, Keokuk, Lake of the Ozarks, Taneycomo, Denison, Buchanan, Lexington, Lloyd Shoals, Williams, Issaqueena, Conchas, San Carlos, Mead, Imperial Dam, Possum Kingdom, Guernsey, Pardee, Bullard's Bar, and John Martin Reservoirs.

(2) Reservoir surveys with suspended-load measurements upstream--Suspended-sediment measurements upstream, corrected to include bed load, provide an index of the total rate of sediment production. The reservoir survey shows what proportion of this is trapped. This type of study was used for Corpus Christi Reservoir during the 1934-1942 period and for Hadley Creek Desilting Basin.

(3) Reservoir surveys with suspended-load measurements up and downstream--In these cases the method used is similar to that described under (1). The suspended-load measurements upstream from the reservoir provide an additional check on the total sediment load of the stream, and (when corrected to include bed load) should equal the sum of the sediment deposited in the reservoir and that measured as passing the dam. This method was used for Marinuka, Wilson, Norris, Hiwassee, T and P, Corpus Christi (1942-1948), Arrowrock, and Hales Bar Reservoirs.

(4) Suspended-load measurements up and downstream with no reservoir survey--Suspended-load measurements upstream from the reservoir provide a measure of the total sediment load. Suspended-load measurements downstream show what proportion of the sediment passes the dam, and the difference is what is trapped. This method was used for Fort Peck Reservoir.

(5) Reservoir surveys with turbidity measurements downstream--This method is similar to that described under (1), except that turbidity records are substituted for suspended load records.

For the fine sediment which is carried over a dam or through outlets in suspension, turbidity measurements are often of sufficient accuracy for use in determining sediment load. A number of simultaneous suspended-load and turbidity measurements are usually taken, in order to establish a correction factor for use with turbidity records. This type of study was made on Decatur, Rockwell, Michie, and White Rock Reservoirs.

(6) Reservoir survey and observation of outlet--In this type of measurement it is known by observation that no water or sediment has ever been discharged over the spillway or through outlets in the dam. The only water losses have been through evaporation and seepage. In such cases the sediment measured in the reservoir represents the total load of the stream, and the trap efficiency is 100 pct. This method of study was used on the H. Lage Pond, Iowa.

(7) Comparative reservoir surveys--This method is typified by the Lake Halbert reservoir system, Texas. Lake Halbert lies at the lower end of a drainage area in which are located 11 small reservoirs. Lake Halbert has a very high capacity-watershed ratio and capacity-inflow ratio, and undoubtedly has a trap efficiency close to 100 pct. In addition, some sediment is trapped in the upstream reservoirs. The system of reservoirs as a whole may therefore be assumed to trap virtually all of the sediment that reaches it. By comparing the annual rate of sediment accumulation per square mile for a particular reservoir with that for the whole system of reservoirs, and assuming that the rates of sediment production are uniform throughout the system, its trap efficiency may be determined.

It is necessary, in taking suspended-load measurements downstream from a dam, to take them as near the dam as possible, because streams tend to pick up a new sediment load quickly downstream from reservoirs by scouring and degrading their channels. For example, as **BROWN** [1950b] has pointed out, the average sediment concentration in the Colorado River below Hoover Dam as of 1947 increases from 0.006 pct 12.8 miles below the dam to 0.091 pct 98.6 miles below the dam, or 15 times. Such a change can cause grave errors in computations of trap efficiency if suspended-load measurements far downstream from the dam are used.

It is also necessary to take dredging into account in computing trap efficiency. Since areas dredged in a reservoir usually fill with sediment again in a short time, dredging tends to increase the amount of sediment trapped in a reservoir. In studying Lake Marinuka, Wisconsin, for example, amounts of sediment dredged from the lake were excluded from the computations of sediment trapped.

Note in Table 1 that reservoirs and ponds of all sizes have been used, ranging from a farm pond with 0.038 sq mi drainage to Imperial Dam Reservoir, draining 184,600 sq mi. The chief criteria in selecting reliable records were accuracy with which trap efficiency could be determined and the availability of information on the various factors which affect trap efficiency. As **GOTTSCHALK** [1948] has stated, the laws of sediment deposition are the same for all types of reservoirs, including stock ponds. Likewise, the trap efficiency of reservoirs is affected by the same factors, regardless of the size of the reservoir.

It has long been recognized [**BROWN**, 1950b] that capacity-inflow (C/I) ratio would be a more accurate index of trap efficiency than the capacity-watershed (C/W) ratio which has heretofore been so widely used. The C/W ratio must be used within definite hydrologic regions, and not as an index of comparison over the country as a whole, for, as is obvious, with the same C/W ratio the trap efficiency will increase as the runoff per unit area decreases.

The main objection in the past to the use of the capacity-inflow ratio has been that records of inflow are lacking for some existing reservoirs. In an effort to get around this difficulty, the annual runoff map shown in Circular 52 of the U. S. Geological Survey was used to estimate the runoff from the few reservoir watersheds where detailed inflow records are lacking. The capacity-inflow (C/I) ratio was then computed in terms of acre feet of storage capacity per acre foot of annual water inflow. C/I ratios are shown in Table 1 along with other pertinent data for the reservoirs used in this study.

Discussion of results

Normal Ponded Reservoirs--The records from Table 1 have been plotted in Figure 6. Note that the correlation for normal ponded reservoirs (conventional reservoirs as distinguished from desilting basins and dry reservoirs), operated without any special efforts at sluicing sediment, is much better using the C/I ratio than using the C/W ratio, as was done in Figure 3.

Records 32-37a represent reservoirs such as Fort Peck Reservoir and Lake Mead which have C/I ratios greater than 1.0. In other words, these reservoirs have a capacity larger than the annual

Table 1--Representative records

Record	Reservoir	Stream	Location	Drainage area
				sq mi
	Normal ponded reservoirs			
1	Williams	E. Fork White R.	Williams, Ind.	4,700
2	Lake Halbert (Rock Res. 1)	Elm Creek	Corsicana, Tex.	5.37
3	Lake Halbert (Rock Res. 3)	Elm Creek	Corsicana, Tex.	1.52
4	Hales Bar (1935-1936)	Tennessee R.	Chattanooga, Tenn.	21,790
5	Hales Bar (1938)	Tennessee R.	Chattanooga, Tenn.	21,790
6	Hales Bar (1937)	Tennessee R.	Chattanooga, Tenn.	21,790
7	Keokuk	Mississippi R.	Keokuk, Iowa	119,000
8	Lake Taneycomo	White R.	Forsyth, Mo.	4,610
9	Wilson Lake	Tennessee R.	Florence, Ala.	30,750
10	Lake Marinuka	Beaver Creek	Galesville, Wis.	138.6
11	Lake Decatur	Sangamon R.	Decatur, Ill.	906
12	Bullard's Bar	No. Fk. Yuba R.	No. San Juan, Calif.	480
13	Lake Halbert (Earth Res. 1)	Elm Creek	Corsicana, Tex.	1.13
14	Lake Rockwell	Cuyahoga R.	Kent, Ohio	205.5
15	Corpus Christi (1942-1948)	Nueces R.	Corpus Christi, Tex.	16,800
16	Corpus Christi (1934-1942)	Nueces R.	Corpus Christi, Tex.	16,800
17	Lexington	Leonard's Creek	Lexington, N. C.	6.83
18	Lloyd Shoals	Ocmulgee R.	Jackson, Ga.	1,414
19	Lake Michie	Flat River	Durham, N. C.	167.5
20	Lake Issaqueena	Six-Mile Creek	Clemson, S. C.	14.02
21	Guernsey	North Platte R.	Guernsey, Wyo.	16,200
22	Arrowrock	Boise River	Boise, Idaho	2,170
23	T and P	Town Creek	Weatherford, Tex.	6.24
24	Hiwassee	Hiwassee R.	Murphy, N. C.	968
24a	Imperial Dam (1938-1942)	Colorado R.	Yuma, Ariz.	184,600
24b	Imperial Dam (1943-1947)	Colorado R.	Yuma, Ariz.	184,600
25	Lake of the Ozarks	Osage R.	Bagnell, Mo.	14,000
26	Pardee	Mokelumne R.	Buena Vista, Calif.	430
27	Possum Kingdom	Brazos R.	Palo Pinto, Tex.	14,098
28	White Rock	White Rock Creek	Dallas, Tex.	99.1
29	Buchanan Lake	Colorado R.	Burnet, Tex.	21,000
30	Norris	Clinch R.	Norris, Tenn.	2,912
31	Senecaville	Wills Creek	Senecaville, Ohio	121
32	H. Lage Pond	Small Branch	Aspinwall, Iowa	0.038
33	Denison	Red River	Denison, Tex.	38,291
34	Lake Mead	Colorado R.	Boulder City, Nev.	167,800
35	San Carlos	Gila River	Globe, Ariz.	12,900
36	Conchas	So. Canadian R.	Tucumcari, N. M.	7,350
37	Fort Peck	Missouri River	Fort Peck, Mont.	57,725
37a	Elephant Butte	Rio Grande	Hot Springs, N. M.	25,923
	Desilting basins			
38	All-American Canal	Colorado R.	Yuma, Ariz.	184,600
39	Hadley Creek, New	Hadley Creek	Kinderhook, Ill.	77
	Semi-dry reservoirs			
40	John Martin	Arkansas R.	La Junta, Colo.	18,933
41	Senecaville (1936-1939)	Wills Creek	Senecaville, Ohio	121

[a] C/W is capacity-watershed ratio in acre feet per square mile. [b] Capacity-inflow ratio in acre

[c] Figures in brackets refer to trap efficiency with sluicing or venting operations in effect.

of reservoir trap efficiency

Period of record	Average annual sediment prod. per sq mi of drainage area	C/W^a	Average annual inflow	C/I^b	Trap efficiency^c	Reference
yr	ton	ac ft/ sq mi	ac ft/ sq mi		pct	
9.3	434	1.19	747	0.0016	0	
69	8480	1.16	399	0.0029	2.3	(20)(4)
69	8480	1.63	399	0.0041	5.8	(20)(4)
2.00	306	6.46	1260	0.0051	30.5	(18)(14)
1.00	306	6.39	1260	0.0051	29.7	(18)(14)
1.00	306	6.41	1260	0.0051	25.7	(18)(14)
23	219	3.43	370	0.0093	50.0	(10)(12)(5)
22.4	494	7.34	783	0.0094	56.3	(22)
2.25	242	17.3	1190	0.0145	44.9	(18)(4)(14)
72	272	8.5	549	0.0155	65.4	(10)(11)
24.2	341	18.9	560	0.0338	78.0	(8)(10)(6)(5)(11)
19.2	504	62.9	1660	0.0378	83.4	(9)
69	8480	15.1	399	0.0378	69.3	(20)(4)
36	117	34.5	698	0.0494	85.8	(11)
6.0	65.0	2.48	45.8	0.0541	73.7	(7)
7.6	65.0	2.92	45.8	0.0638	76.7	(7)
4.7	851	66.1	907	0.0730	77.2	(4)
24.3	653	74.6	923	0.0807	81.4	(26)(2)(13)
8.75	408	74.5	747	0.0998	86.3	(25)(2)(13)
11.4	1569	125	987	0.127	94.2 [84.1]^c	(40)(27)(4)
20	292	11.2	74.2	0.151	92.2	(29)(23)
32.64	475	127	742	0.171	93.0 [90.3]^c	(28)
8.5	1217	55.9	293	0.191	87.0	
0.75	503	453	1660	0.273	98.1	(18)(14)
5.0	2170	11.7	55.5	0.211	90.2	(4)(23)(1)
5.0	2170	3.81	55.5	0.0686	72.3	(4)(23)(1)
17	580	145	498	0.292	96.7	(33)
14	217	488	1560	0.313	95.0	(9)
7.75	650	49.9	63.4	0.787	98.0	(21)
25	2104	74.6	202	0.812	99.3	(24)(2)(13)
7.1	216	44.7	53.3	0.837	98.6	(4)
0.75	422	918	970	0.946	99.1	(18)(4)(14)
5.1	1026	727	768	0.947	94.3	(37)(10)(6)(5)(11)
11.0	6270	318	261	1.22	100.0	(17)
6.2	723	151	108	1.40	100.0	(34)(5)
13.25	1044	189	77.3	2.44	99.4	(39)(2)(4)(6)(5)(23)
18.19	601	96.0	26.7	3.59	98.0	(31)(2)(4)(23)(6)
10.3	512	104	27.2	3.82	97.3 [95.8]^c	(32)(36)(23)
12	120	337	72.5	4.65	100.0	(38)(35)(12)
32.33	854	93.2	45.4	2.05	98.6	(30)(23)(2)(4)
10.0	406	0.061	55.5	0.0011	91.7	(4)(6)
5.01	2490	36.7	432	0.0850	98.8	(11)
5.4	450	36.3	21.3	1.71	62.2	(4)
3.2	1026	731	768	0.953	48.4	(37)(10)(6)(5)(11)

feet of capacity per acre foot of annual inflow.

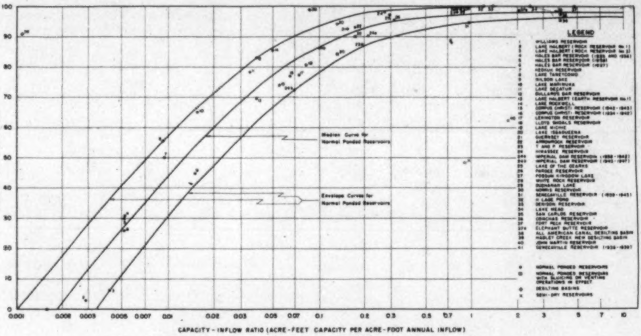

Fig. 6--Trap efficiency as related to capacity-inflow ratio, type of reservoir, and method of operation

runoff from their watersheds. When the effects of evaporation and seepage are also considered, it is obvious that water will rarely be spilled over the dams of such reservoirs, and that their trap efficiency must therefore be close to 100 pct.

The C/I ratio thus provides a means of differentiating between the "holdover storage reservoirs" and "seasonal storage reservoirs" described by **MADDOCK** [1948]. Reservoirs with a C/I ratio of 1.0 or less may be classed as seasonal storage reservoirs, and those with a ratio greater than 1.0 as hold-over storage reservoirs.

The C/I ratio is a combination of the C/W ratio and annual inflow. The C/I ratio, in acre feet of capacity per acre foot of annual inflow, may be obtained by dividing the C/W ratio, in acre feet per square mile of drainage area, by the annual inflow, also in acre feet per square mile of drainage area.

Reservoirs may have very different C/W ratios and annual inflows, yet have the same C/I ratio, and the same trap efficiency, other factors being equal. For instance, a reservoir in the more humid part of the country may have a C/W ratio of 100, an annual inflow of 1000 acre feet per square mile, and a C/I ratio of 0.1. Another reservoir in a more arid region may have a C/W ratio of 10, an annual inflow of 100 acre feet per square mile, and the same C/I ratio, 0.1. Both reservoirs, assuming they are of the normal ponded type, will have roughly the same trap efficiency (around 87 pct, from Figure 6).

Theoretically, no reservoir can have a trap efficiency of zero per cent until its capacity is reduced to zero or the runoff approaches an infinite quantity. Similarly, a trap efficiency of 100 pct is theoretically impossible until the capacity reaches an infinite quantity or the runoff reaches zero. Actually, an inspection of Table 1 and Figure 6 shows that there are several instances on record of trap efficiencies of zero and 100 pct.

For example, Williams Reservoir, a power reservoir near Williams, Indiana, was built in 1911. In 1930 cross sections were established by the Corps of Engineers, and in 1939 these cross sections were re-run by the Soil Conservation Service. This reservoir, which has a very low C/W ratio (1.19) and C/I ratio (0.0016), probably trapped some sediment between 1911 and 1930. During the period of measurement, however, from 1930 to 1939, there was a net scour of 275 acre feet, or an increase in capacity of 5.0 pct. Thus the trap efficiency was less than zero for this period. It appears probable that reservoirs of very low C/I ratio may alternately fill and scour, depending upon stream-flow conditions, and may thus have a trap efficiency of zero or less during periods of scour.

The three instances of measured trap efficiency of 100 pct are at the H. Lage Pond, Fort Peck Reservoir, and Denison Reservoir. The Lage Pond, as previously mentioned, has never spilled over, and the only water losses which have occurred have been through evaporation and seepage.

In regard to Fort Peck Reservoir, a letter dated May 3, 1951, from the Fort Peck District Office, Corps of Engineers, Fort Peck, Montana, states as follows:

> Water sediment samples are obtained periodically at the tunnel outlets and the spillway discharge channel and analyses of these samples have disclosed that the amount of sediment discharged from the reservoir is quantitatively negligible. On this basis, therefore, the trap efficiency of the Fort Peck Reservoir may be considered to be approximately 100 pct.

Similarly, a letter dated May 9, 1951, from the Tulsa District Office, Corps of Engineers, Tulsa, Oklahoma, states:

> There has been no significant sediment outflow from Denison Reservoir since the normal pool was filled in 1945, so its trap efficiency to date is virtually 100 pct. No density currents have been observed to pass entirely through the reservoir up to the present time.

Since this date, however, at least one density current has been observed to pass completely through the reservoir and reach the outlets of Denison Dam.

Hence, it is obvious that if inflow is not sufficient to counteract water losses by evaporation and seepage, there will be no water or sediment losses over the spillway or through outlets, and the trap efficiency will be actually 100 pct. Similarly, if water inflow is so low that water releases can be made only rarely, the velocity of the water through the reservoir will be very low. Practically all of the sediment load will settle out, and what little water is released will be essentially clear. In such cases the trap efficiency may be considered virtually 100 pct.

Sluicing and venting--In Table 1 and Figure 6 are also shown the effects of various attempts to sluice or vent additional amounts of sediment from reservoirs. At Arrowrock Reservoir, Idaho, sluicing out sediment deposits through the bottom outlets or sluice gates during periods of relatively low discharge is estimated to have reduced the trap efficiency from 93.0 to 90.3 pct, and to have increased the sediment loss from the reservoir by 39 pct [SEAVY, 1948a]. The average discharge below Arrowrock Dam for 33 years has been 2230 cu ft/sec, as compared with an average discharge of only 605 cu ft/sec on the 270 days during which sluicing operations were conducted. The fact that sluicing was carried on only during periods of low stream discharge and low sediment concentrations is probably the major reason for its low effectiveness in removing sediment from the reservoir. Future sluicing operations are not contemplated because of possible downstream damage to fish and to the proposed Lucky Peak Dam.

At Conchas Reservoir, New Mexico, sluicing has been carried on whenever sufficient water has been available, from 1942 to 1948. Ordinarily, sluicing has been done during periods of low discharge. No large floods occurred during this period, but it was noted that on several occasions when the conduits were open during smaller floods, "the sediment content of the discharge continued to remain at a much higher value than usual for as much as several days, indicating that some of the sediment was possibly furnished from a density flow through the reservoir" [U. S. CORPS OF ENGINEERS, 1950a].

Sluicing operations have decreased the trap efficiency of Conchas Reservoir from an estimated 97.3 to 95.8 pct, and have increased the sediment loss from the reservoir by 56 pct. The relatively low effectiveness is probably due largely to the fact that no effort has been made to time sluicing operations to intercept gravity underflows and thus pass heavily sediment-laden water out of the reservoir. That sluicing has been more effective than at Arrowrock Reservoir is a reflection of the fact some gravity underflows were accidentally encountered. The Conchas Reservoir study indicates that flushing to remove sediment that has already settled is ineffective except immediately upstream from the sluice intakes. Sluicing operations are expected to be discontinued when water can no longer be spared from irrigation projects.

At Lake Issaqueena, Clemson, S. C., venting of sediment-laden water through a gate near the base of the dam was carried on from August, 1940, to April, 1942 [ZWERNER, and Others, 1942]. Just after the flood of August, 1940, the suspended matter concentration in flow coming from the outlet pipe was 552 ppm, while that passing over the spillway was 183 ppm. Gravity underflows were intercepted and passed through the dam during nine periods of storm runoff.

The trap efficiency of the lake was lowered from 94.2 to 84.1 pct by these venting operations. The sediment loss from the lake was increased by 174 pct. As stated by BROWN [1944], it seems clear from the observations that if the gates had been opened according to a pre-arranged plan governed by forecasting flood flows in the drainage area, at least ten per cent of the incoming sediment, and possibly as much as 25 pct, could have been vented through the two outlets, without adversely affecting water storage in the lake.

It appears, therefore, that sluicing or venting operations have much better chances of accomplishing their purpose when they are timed to intercept gravity underflows as they reach the dam. If gravity underflows are not present, such operations should at least be timed to meet the higher sediment concentrations brought in by flood flows. It is likely that accurate timing to intercept gravity underflows can treble or quadruple the amount of sediment lost from the reservoir.

Desilting basins--The trap efficiency of desilting basins is governed largely by their shape. Hadley Creek New Desilting Basin, Illinois, for example (Table 1 and Fig. 6) covers 280 acres but has an average effective depth of less than four feet. A normal ponded reservoir with the same C/I ratio would have a trap efficiency of about 85 pct. This basin, however, traps 98.8 pct of the sediment reaching it, largely because of its shallowness and the small interval of time required for the sediment to reach the bottom. There are other factors, such as the coarse nature of the incoming sediment and the location of the desilting basin at a point where the stream gradient decreases abruptly.

An even more efficient type of desilting basin is exemplified by the All-American Canal Desilting Basins, Arizona (Table 1 and Fig. 6). In this case, method of operation, in addition to the other factors mentioned, greatly influences the trap efficiency. These basins are equipped with rotary scrapers which deposit the sediment in collecting trenches [BROWN, 1944]. Thence it is forced into a system of sludge-disposal piping and carried back to the river below. A normal ponded reservoir with a C/I ratio as low as these basins could be expected to have practically no trap efficiency at all, and yet the basins trap 91.7 pct of the sediment reaching them.

Thus, desilting basins may be expected to have trap efficiencies above 90 pct in a much lower range of C/I ratios than for normal ponded reservoirs (Fig. 6). Without mechanical removal of sediment, such high trap efficiencies may extend downward to a C/I ratio of around 0.02. With mechanical removal, they may extend much lower, even to 0.001.

Dry reservoirs--Although no information is available on the trap efficiency of truly dry reservoirs such as those in the Miami Conservancy District, Ohio, two reservoirs which have been operated in a semi-dry condition provide some suggestive figures (Table 1 and Fig. 6).

Senecaville Reservoir, Ohio, for example, a flood-control reservoir, was completed in October 1936 [U. S. ENGINEER OFFICE, 1945] but not put into operation until early in 1940. A small lake was established by the structure with the gates wide open. A sedimentation survey was made in December 1939 and another in March 1945. The first survey showed a much lower rate of sediment accumulation than the second, although the annual runoff was higher during the first period, and the rate of sediment production from the watershed is assumed to have been approximately the same for both periods (Table 1). These surveys, supplemented by suspended-load measurements at the dam from January, 1939, to January, 1942, indicate that the trap efficiency was much lower during the first period (48.4 pct) than during the second period (94.3 pct). An examination of the history of the reservoir suggests the cause. Although the reservoir has a total capacity of 88,500 acre feet, it was held near 3700 acre feet prior to December, 1939, because much of the land in the basin had not yet been purchased. As a result, most flows were passed unrestricted through the reservoir, and much sediment was also carried through. After 1939, the conservation pool was raised to 43,500 acre feet, with much greater volumes of water being held during flood periods. Hence the trap efficiency increased markedly.

John Martin Reservoir, Colorado, is another example of a reservoir which has been operated in a semi-dry condition. This flood control and irrigation reservoir was completed in 1943, with a total capacity of 701,200 acre feet. Since that time it has frequently been dry, and has never during the period of this study (1943-1948) stored more than 244,700 acre feet of water. Much water and sediment has consequently been passed through the dam with little restriction, and the trap efficiency is unusually low, 62.2 pct, for a reservoir with such a high C/I ratio (1.71).

Thus it is apparent that even hold-over storage reservoirs like John Martin, if operated so as to allow large flows of water to pass through the dam, may have trap efficiencies in the 60 pct range rather than above 90 pct as would be expected with normal operation. Reservoirs with lower C/I ratios, operated in a similar manner, may be expected to have still lower trap efficiencies. Truly dry reservoirs, such as the Miami Conservancy District reservoirs, undoubtedly have much lower trap efficiencies, probably in the ten to 40 pct range, depending chiefly upon C/I ratio.

Although the relationship shown in Figure 6 between trap efficiency and C/I ratio appears to be reasonably good for normal ponded reservoirs without sluicing operations in effect, it is apparent that a great deal of additional work is required in the field of reservoir trap efficiency.

Particularly, field studies are needed on dry reservoirs and on the various types of desilting basins. Further field and laboratory studies are also needed of the feasibility of venting gravity underflows and high sediment concentrations from various types of reservoirs.

Conclusions

The more important conclusions reached in this study are as follows:

(1) The capacity-inflow (C/I) ratio offers a much closer correlation with reservoir trap efficiency than the capacity-watershed (C/W) ratio heretofore widely used, because it affords a measure of not only the relative capacity, but also the runoff from the watershed.

(2) The C/I ratio also provides an index to the type of reservoir; that is, reservoirs with C/I ratios of 1.0 or less may be classed as seasonal storage reservoirs, and those with a ratio greater than 1.0 as hold-over storage reservoirs.

(3) Although theoretically no reservoir can have a trap efficiency of zero or 100 pct, under actual field conditions true trap efficiencies of zero or 100 pct are sometimes found.

(4) Efforts at sluicing or venting sediment from reservoirs vary in effectiveness. At Arrowrock Reservoir, where the sluicing was done entirely during low discharge periods, the sediment loss from the reservoir was increased by 39 pct. At Lake Issaqueena, where venting was partially timed with gravity underflows through the lake, the sediment loss was increased by 174 pct. It appears likely that accurate timing of venting operations to intercept gravity underflows can treble or quadruple the amount of sediment lost from a reservoir.

(5) Desilting basins, largely because of their shape, have much higher trap efficiencies than normal ponded reservoirs. For desilting basins not equipped for mechanical removal of sediment, trap efficiencies above 90 pct appear to prevail with C/I ratios as low as 0.02. With mechanical removal of sediment, such high trap efficiencies may be found in even lower C/I ratio ranges, as low as 0.001.

(6) Semi-dry reservoirs may be expected to have much lower trap efficiencies than normal ponded reservoirs. Even hold-over storage reservoirs like John Martin, if operated so as to allow large flows of water to pass unrestricted through the dam, may have trap efficiencies in the 60 pct range rather than above 90 pct, as would be expected with normal operation. Truly dry reservoirs, such as those in the Miami Conservancy District, probably have trap efficiencies in the ten to 40 pct range, depending upon C/I ratio.

(7) Further field and laboratory studies are needed, particularly on the trap efficiency of desilting basins and dry reservoirs and on the feasibility of venting gravity underflows from various types of reservoirs.

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INDICATORS OF EROSION ON WATERSHED LAND IN CALIFORNIA

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Abstract--A need is recognized for qualitative criteria by which to judge the occurrence of erosion on watershed land. This paper discusses geologic and accelerated erosion, some factors that affect erosion, and some methods of appraising erosion. The paper then describes some indicators that may be applied by observation in disturbed and undisturbed areas to help an observer judge whether or not erosion has been accelerated.

In the course of forest influences studies in watershed management a survey has been made to determine the effect of watershed denudation upon erosion in mountain and foothill areas. Development of a set of erosion indicators was found necessary, as a first step in the survey, to allow the consistent and definite appraisal of erosion. The full appraisal of erosion has three phases: (1) recognition of active erosion, (2) determination of its cause, and (3) appraisal of the damage done by it. This paper is concerned with the recognition of erosion. The determination of its cause and the appraisal of its damages require separate treatment. The erosion indicators described in this paper were developed in areas denuded by fire, but most have been found to apply equally well in areas disturbed by other agents.

When active erosion is recognized, the question immediately arises: Is this a natural condition, or is it the result of some watershed disturbance? If it is a natural condition of geologic erosion, the chances are that it can be remedied only at great cost. If it is an abnormal condition of accelerated erosion, it can probably be prevented or remedied at reasonable cost, provided action is taken soon enough. The two processes differ mainly in the rate at which they occur, and in man's ability and need to control them. Both kinds of erosion have been clearly illustrated by SHARPE [1938], and recently discussed by BENNETT and Others [1951].

Geologic erosion is generally recognized as the gradual wearing away of the land surface by the action of water, wind, and gravity, under natural conditions. It is defined more specifically by MILLER [1928] as: ". . .the breaking up, decay, and transportation of materials at and near the Earth's surface by weathering and solution, and by the mechanical action of running water, waves, moving ice, or winds which use rock fragments as tools."

Geologic erosion proceeds so slowly, in most places, as to go practically unnoticed. The fact that residual soil exists on sloping land is evidence that under natural conditions the process of erosion is even slower than the extremely slow process of soil formation. Under natural conditions, normal geologic erosion rates may change with change of climate, or with elevation or subsidence of the land. Except for the local activity associated with sudden volcanic and tectonic upheavals, however, such changes take place so slowly as almost to be unrecognized because the alteration may occur over hundreds or thousands of years.

Accelerated erosion, on the other hand, proceeds rapidly. Many of its processes take place before our very eyes. It is defined by SAMPSON [1952] as "Abnormally rapid removal of soil -- 'man-induced' erosion . . ." The activities of man frequently accomplish in days or weeks an acceleration in the rate of erosion that might require hundreds or thousands of years under natural conditions. Accelerated erosion is of great consequence because it removes topsoil, lowers soil fertility, causes rapid sedimentation of reservoirs built to store water, and increases the damage done by floods. By poor practices in cultivating, burning, grazing, logging, and building roads, or otherwise disturbing the land surface, man creates conditions that favor accelerated erosion.

Destruction of the vegetal canopy and litter leaves the soil surface without protection against the agents of erosion. In bare areas, rain can strike the soil with full force, wind can act with undiminished velocity, and gravity can cause dry-sliding on steep slopes. The plant roots are seldom damaged to a great extent by such disturbances as grazing and fire, and they remain underground to help stabilize the soil mass. But erosion begins at the soil surface; protection above ground is also needed to prevent soil loss. The function of the canopy and litter can be better understood by considering the effect of raindrops falling on bare soil.

The bomb-like impact of raindrops on bare soil has been shown by **ELLISON** [1950], who demonstrated that detachment and transport of soil particles by raindrop splash are the initial steps in the erosion process. Erosion by downslope creep was found to occur through the action of splash alone, while the soil losses were increased greatly when raindrop splash and surface runoff acted together. Ellison's studies confirmed the reduction of infiltration capacity and increase of surface runoff caused by turbidity of surface flow, as reported by **LOWDERMILK** [1930], and showed splash erosion to be an important cause of the turbidity. By contrast, Ellison found that areas having a grass cover and litter to break the force of falling raindrops suffered low erosion losses and maintained high infiltration capacity.

Erosion occurs at different rates in different areas, owing to several variables. Rainfall intensity is an important variable, as erosion cannot occur unless the rain is heavy enough to detach and transport particles of soil. For instance, an inch of rain falling gently over a 24-hour period might cause no appreciable soil movement whereas the same amount of rain falling in ten minutes might cause severe erosion. Other variables are the ease of detachment and transport of soil particles, which differ with different soils. Still another is steepness of slope. For these reasons, erosion may not always occur in denuded areas, and when it does occur, the evidence may be obvious or obscure.

Recognizing anything but obvious erosion requires close observation, the use of definite criteria, and often the evaluation of several indicators of soil movement. Moreover, to decide whether or not erosion has been accelerated will require that the same criteria be applied to disturbed and undisturbed areas that are adjacent. The areas should be comparable as to slope, soil, and topography, and they should have been exposed to the same conditions of rainfall and wind. The same plant cover should have been present in both areas before disturbance.

Sedimentation surveys of reservoirs are probably the most accurate means of measuring the erosion activity of an entire watershed over a period of years. But reservoirs seldom exist in the locations desired for erosion measurement on a specific parcel of land. Moreover, sediment from disturbed areas may require several years to reach a reservoir. And after sediments have been deposited, it is usually difficult to separate the stream channel sediments from those that came from the watershed slopes. For these reasons, although the nature of sediments gives clues to their source, reservoir surveys often fail to show the effects of a single land disturbance.

The character of soil profiles on slopes and valley floors may give information on the erosion history of an area. Such profiles are frequently exposed in cut banks along roads and streams, or they can be sampled by boring with a soil auger. In flood plains, coarse-textured deposits lying above fine-textured layers are recognized indicators of accelerated erosion [**KITTREDGE**, 1948]. However, where the topography is youthful and the soil material on the slopes is only a few inches deep there is apt to be no profile development. This is the case in many of the mountain watersheds of California. Where a profile has been developed, the soil loss after a single disturbance may be too small to show. For these reasons the study of soil profiles is apt to be unsatisfactory in revealing the effects of current land disturbances.

Study of the ground surface, on the other hand, will show in a qualitative way whether or not erosion is occurring. There are many easily recognized indicators of soil movement on top of the ground, and this evidence is significant in evaluating the effects of watershed denudation. Examinations made in fair weather bring out certain kinds of evidence; examinations made in rain or windstorms often bring out other kinds. Some evidence, such as muddy runoff, is obvious. Other evidence, such as erosion pedestals, may require close observation to be detected. Still other evidence, such as unscorched collars on surface rocks, has been found undependable. Recognizing active or recent erosion on slopes requires the use of some indicators that are different from those used in stream channels. At each examination point it is important to seek confirming evidence, so that conclusions as to the occurrence of erosion may be based on two or more indicators. A case has seldom been observed in which the evidence of erosion was limited to a single indicator; usually several can be found.

Some common indicators of erosion are discussed below and illustrated in the Figures. Use of these indicators will aid in recognizing accelerated erosion. The indicators have been classified according to their occurrence on slopes and in stream channels. Some indicators of soil stability have also been defined.

Erosion indicators observed on slopes

Indicators of erosion that may be observed while examining the slopes of a watershed are grouped by the common agents of erosion -- water, wind, and gravity.

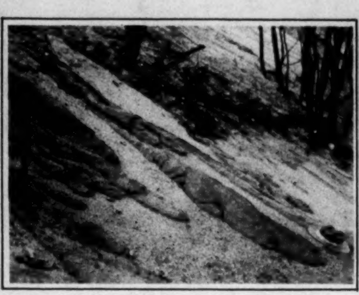

Fig. 1--Mud flows; photo by C. J. Kraebel

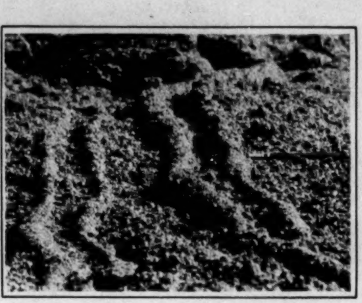

Fig. 2--Lateral ridges

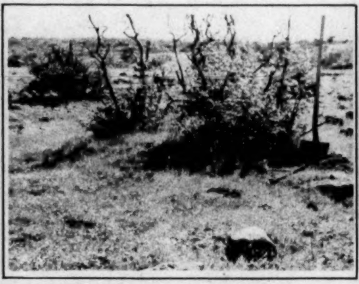

Fig. 3--Mounds of residual soil

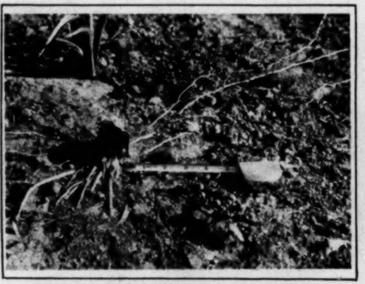

Fig. 4--Unscorched stems and exposed roots; scale in inches

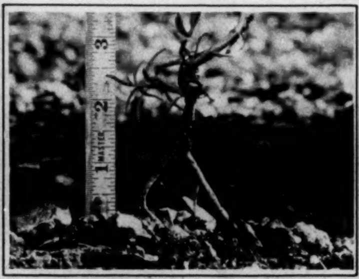

Fig. 5--Stilt-like roots; scale in inches

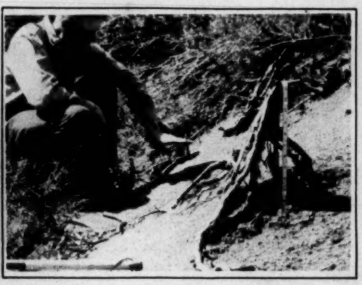

Fig. 6--Exposed root crowns

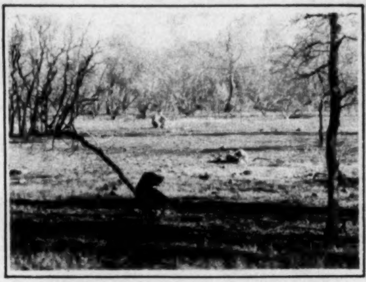

Fig. 7--Deposits of soil on gentle slopes

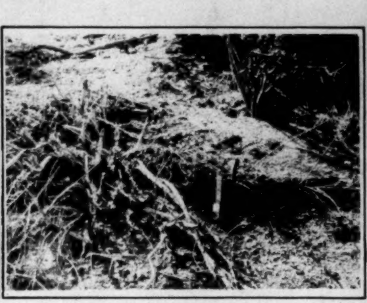

Fig. 8--Benched deposits

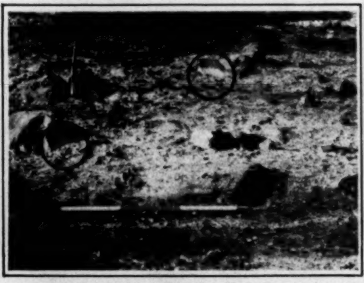

Fig. 9--Light-colored collars on rocks (within circles)

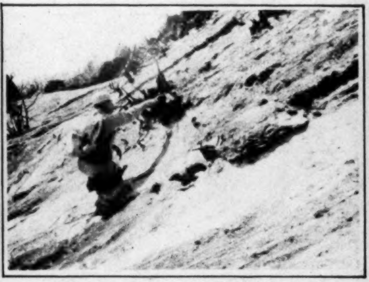

Fig. 10--Exposed bedrock

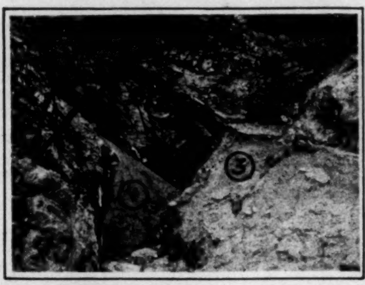

Fig. 11--Sliding gravel and sand; the painted stick is three feet long

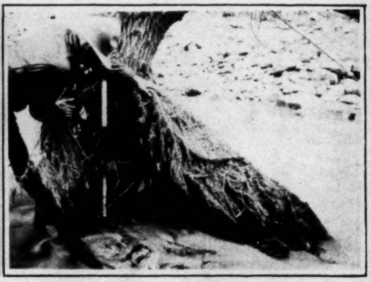

Fig. 12--Gouged channels

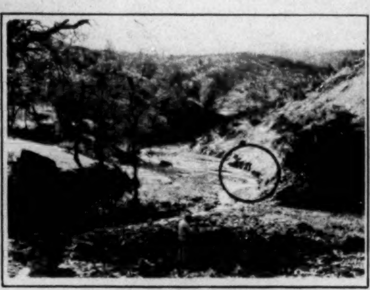

Fig. 13--Gravel and sand in channels; undercut stream banks

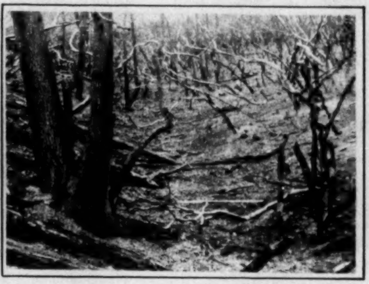

Fig. 14--Rounded drainage bottoms

Erosion by water--Muddy water flowing over the soil surface is an obvious indicator of erosion that is currently active. Mud flows that slide downhill on top of the ground (Figure 1) are also obvious indicators of erosion. Because such mud flows form and run their courses in the space of a few minutes during heavy rain storms, they are not frequently observed in action. Sometimes, however, the rain stops before the flows have run their courses; then they may be found "frozen" in place.

Lateral ridges of mud (Figure 2), literally forming gullies on top of the ground, are left behind the mud flows shown in Figure 1. Such ridges may define the course of future rills and gullies. In the long, rainless summer that characterizes California, however, the ridges may be erased by the action of wind, gravity, and animal disturbance.

Rills are small water channels cut by minor concentrations of runoff. Rills are clear evidence of soil loss which may be severe, especially when the rills are associated with sheet erosion. Sustained runoff will enlarge rills to gullies. In prolonged dry periods, however, rills may be erased by wind and other disturbances, leaving little evidence of erosion.

Shoestring gullies are frequently formed during a single storm in areas that have been suddenly denuded of vegetation. Gullies are one of the most widely recognized indicators of erosion because they are usually visible from a distance and because the soil loss is obvious.

Pebbles perched on necks of undisturbed soil are evidence of sheet erosion, but close observation may be required to detect them. In burned areas the upper sides of the pebbles will often be blackened while their lower sides, in contact with the soil, will show the normal color of the stone. Sometimes the erosion necks, or pedestals, are capped by fallen leaves, clumps of moss, twigs, or even fallen limbs.

Erosion pavement is a layer of rock fragments on the ground surface, similar in kind, size, and shape to the rock fragments embedded in the soil beneath the surface. The pavement is formed when the finer particles of surface soil are washed or blown away, leaving behind the larger fragments. This process is usually so slow that the increase in the number of stones brought about by erosion following a single disturbance is not ordinarily discernible. The pavement indicates accelerated erosion, except possibly in desert areas where geologic erosion is very active.

Mounds of residual soil (Figure 3) may indicate erosion, although the evidence is obscure and requires careful interpretation. Such mounds may be small or large. Perched clumps of grass sometimes constitute evidence of this type on a small scale. The mound covered by scrub oak in Figure 3 is six to eight feet in diameter and indicates erosion on a larger scale. In this case the evidence points to the loss of approximately one foot of soil, undoubtedly over a long period of time. The conclusion that the mound shown was caused by erosion was reached after considering the probable ways in which it could have been formed, as follows: (1) building-up of soil among the oak stems by (a) accumulation of litter and humus, (b) accumulation of soil through rodent activity, (c) deposition of water-borne soil from up the slope, or (d) deposition of wind-blown soil; or

(2) erosion of soil from the areas surrounding the oak clump, and protection of the mound of soil by the oak tops and roots.

The field examination showed that the mound was composed largely of mineral soil with little humus, which checked out possibility (1a); there were no signs of rodent activity, past or present, ruling out (1b); the mound was not stratified by water-borne deposits, which checked out possibility (1c); and throughout its profile, the mound contained rock particles, many of which were too large for deposit by wind; that observation checked out possibility (1d). The remaining possibility, that the mound was a relict of residual soil protected against erosion by the oak shrub, was confirmed by the presence of a well-developed erosion pavement in the area around the mound. This pavement was composed of the same kinds and sizes of rock particles found inside the mound.

Unscorched collars on shrub stems (Figure 4) are usually good indicators of erosion. Fire hot enough to consume the large stem shown would undoubtedly have charred its base if it had not been protected by soil. Roots exposed above ground, also shown in Figure 4, indicate loss of the surface soil in which they grew. Either water or wind may cause such erosion. In an area burned recently, the presence of flammable but unscorched shreds of papery bark on the roots suggests that the soil which gave protection from the flames has been removed since the fire. Rootlets that are exposed but unscorched are good evidence of current erosion. Old roots that have lain long above ground and have lost their papery bark through weathering are not easily scorched; hence they are not as good indicators of current erosion. The evidence in Figure 4 indicates an average soil loss of about one inch since the area was denuded.

The stilt-like roots of the young plant in Figure 5, probably Pentstemon heterophyllus, indicate severe sheet erosion. As there were no rills or gullies in the area, close examination was required to detect this evidence. The plant is estimated to be not more than two or three years old. When the plant began its growth the soil surface was just above the junction of roots and stem. The plant is large and deep-rooted enough to have withstood frost heaving, and there was no evidence of frost action nearby. Thus erosion is indicated which must have occurred within the last two or three years The area was burned eight months before the picture was taken, but the exposed roots are not charred or sooty. For these reasons it is concluded that the erosion occurred after the fire. Confirming evidence of exposed, unscorched rootlets and perched pebbles was found nearby. There is also a well developed erosion pavement.

Shrub root crowns standing above the soil surface (Figure 6) on single or multiple roots often give striking evidence of erosion. In the area pictured, soil loss of five to six inches since the last fire is indicated by the height to which the uncharred portions of manzanita roots extend above the present ground surface. This is about two-thirds of the total erosion indicated. The general appearance of the crown and exposed roots, the sound condition of the wood, and the firm anchorage of the stump suggest that the shrub was probably alive at the time of the last fire, 17 years ago. Such exposed root crowns are often found locally in the chaparral.

Deposits of soil in ditches and hillside depressions are obvious evidences of erosion. In mountainous terrain, an empty ditch that crosses the slope is a good place to look for slope erosion. Abandoned ditches are particularly good because there is no flow of water in them to carry away the eroded material. A ditch that was empty at the time of watershed disturbance and filled with sediment at a later date offers conclusive evidence of erosion during the intervening period.

Deposits of soil on gentle slopes are evidences of erosion which are sometimes hard to detect. Excavation at the bases of oak trees in the foreground of Figure 7 showed 1/2-inch of soil deposited above the char-line from the fire of the previous fall. Source of the eroded sediments was the slope above, in the vicinity of the man in center distance, where exposed but unscorched rootlets gave evidence of half to one inch of sheet erosion in the current winter. There were neither rills nor gullies in the area. Gradient of the slope was from three to five per cent, and grass was rapidly covering the area of deposition. Ash and bits of burned plant material lying on the original ground surface under the new deposit can often be found as confirming evidence in burned areas.

Benched deposits of soil indicate erosion activity (Figure 8). Such benches are often formed by soil sliding or washing down a slope and lodging against obstructions such as rootcrowns, fallen limbs, herbaceous vegetation, or rocks. The downward movement is aided by rainfall, but on steeper slopes it may occur through soil creep and dry-sliding. Because animal activities often cause similar disturbance in limited areas, care should be used in interpreting this evidence. Gradient of the slope in Figure 8 is estimated at 40 pct. Recovery of the chaparral in the 17 years since the area was last denuded has been so slow that 40 to 50 pct of the soil surface has no litter cover. With so little protection for the soil, erosion continues.

Light-colored collars on the sides of rocks just above the ground (Figure 9) often appear to be striking evidence of current erosion, yet this is not always true. The collars are plain on the rocks pictured (circles), but there is no confirming evidence of erosion. In such cases the collars may possibly indicate the depth of litter consumed in a recent fire. Rock collar evidence of erosion is often difficult to interpret, and must be classed as doubtful unless it is supported by other evidence.

Exposure of bedrock or of large rock surfaces (Figure 10) may occur when erosion is severe. Newly exposed surfaces are usually different in color from weathered surfaces. Frequently rocks exposed before a fire will have their surfaces blackened by soot, which is readily recognizable and increases their color contrast with areas uncovered by post-fire erosion. Figure 10 shows bedrock exposed in a single storm that occurred two days after the area was denuded by fire. The man points to the char-line on a brush root crown, which confirms the rock evidence.

Confirming evidence of erosion is always desirable and can frequently be found at a single examination point. Experience has shown that one indicator, such as a rill, gully, or exposed root, may catch the eye. Close observation may then reveal less obvious indicators, such as perched pebbles and exposed rootlets. On many soils the smooth, compacted surface that results from raindrop impact, puddling, and sheet runoff can be observed in addition to the several indicators.

Erosion by wind--Clouds of dust raised by strong winds are obvious evidence of wind erosion. Observation near the edge of a disturbed area will often show dust blowing from the disturbed slopes but not from adjacent undisturbed slopes.

Unscorched roots lying on top of the ground in burned areas when there has been no rain are dependable but less obvious indicators of wind erosion. In Figure 4, such roots confirm the soil loss indicated by the char-line on the shrub root crown. Confirming evidence of wind erosion such as dust clouds, windrowed soil and gravel, and drifted soil should be sought.

Windrowed soil and gravel, frequently observed on the lee side of obstructions such as fallen brush stems, are an obvious evidence of wind erosion. Wind-swept areas of firm, smooth soil will often be found nearby.

Drifts of soil in road-cuts and in similar depressions are easily observed and unmistakable evidence of wind erosion.

Erosion by gravity--Cones of sliding gravel and sand (Figure 11) that form at the foot of steep slopes are obvious indicators of erosion. This is a surface process, in effect a ravelling of dry soil material from slopes at or above the angle of repose; it is not a form of slumping. Such dry-sliding has been observed in full swing within minutes after a slope was denuded by fire. The force of gravity alone may be enough to start this process, but the action is aided by wind and the movements of animals. The detritus is carried downstream by winter runoff, and frequently no trace of it remains the following spring. Figure 11 shows two such cones of different age, formed during the first winter after the watershed was denuded. At (1) is a cone that was in process of formation on the day the picture was taken, in May following a winter of heavy runoff. At (2) is a cone formed earlier the same winter, and now partly washed away. Also in the picture, at (3), is the remnant of a deposit which filled the channel during the first storms at the beginning of the winter; this deposit was the product of severe water erosion.

Erosion indicators observed in stream channels

Erosion evidence is often easier to recognize in stream channels than on slopes, but it may be more difficult to interpret. This is true because in the watershed above the point of observation there is greater opportunity for the interaction of variables that govern the erosion rate, such as rainfall intensity, soil characteristics, and steepness of slope. Moreover, stream channels contain the evidence of geologic as well as accelerated erosion. And the evidence of a single erosion event, be it geologic or accelerated, may remain in the channel for many years, depending upon the rate at which the deposits are moved downstream by runoff. Inasmuch as this discussion is limited to the recognition of erosion, a few erosion indicators that may be observed in stream channels are described without reference to their cause. Determination of whether the erosion is geologic or accelerated, or a combination of both, must be made after an examination of the watershed.

Muddy streams obviously indicate erosion in the watershed.

Gouged channels (Figure 12) are sometimes marked by the exposed roots of trees. As on the mountain slopes, such roots offer clear evidence that the soil in which they developed has been washed away. The willow roots shown were uncovered in a single flood, after a portion of the watershed was denuded.

Deposits of gravel and sand on roads at canyon crossings are another obvious evidence of erosion upstream. They frequently block roads by plugging culverts and spreading debris over the road surface. Such deposits should be distinguished from those that are often found below cut banks weakened by road construction.

Beds of gravel and sand in stream channels (Figure 13) are signals that erosion has occurred upstream. Careful examination of the watershed is necessary to determine the source of this sediment. Such deposits will not stay in place, but will continue to move downstream. Some of this material may be deposited on valley flood plains, but the bulk of it will eventually be washed into a lake, a reservoir, or the ocean.

Undercut streambanks (Figure 13) show erosion resulting from increased streamflow or, as in the canyon pictured, from meandering of the flow over a streambed filled with detritus. A field examination showed that in this case the sand and gravel were the product of erosion that occurred soon after the watershed was denuded.

Sediment in reservoirs is evidence of erosion in the watershed. Source of the sediment may be the stream channels or the watershed slopes, and the erosion may be either geologic or accelerated. The character and color of the sediment will often give clues to its source, but an upstream examination is required for the identification of source areas.

Indicators of soil stability

Undisturbed litter on watershed slopes, together with a relatively smooth soil surface lacking rills, gullies, or other indicators of recent erosion, is evidence of soil stability; geologic erosion may be proceeding, but there is no evidence of soil movement.

Rounded drainage bottoms on hillsides (Figure 14), together with the absence of undercut banks and channel deposits, are further indicators of stability. For this illustration a denuded drainage was chosen because the evidences of soil stability are not hidden by vegetation. This drainage was denuded in the spring of the year, and little rain had fallen up to the time the photo was taken.

Clean channels of streams are evidence of soil stability in the watershed. Such channels contain little or no sediment, grass often grows close to the water's edge, and the runoff is clear or only a little roily during heavy rain storms.

Acknowledgments

The illustrations are from U. S. Forest Service photographs. Individual credit is given for pictures not taken by the author.

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A METHOD OF FORECASTING LOW FLOW OF STREAMS

H. C. Riggs

Abstract--This paper presents a method of forecasting the discharge of streams during periods of low flow by use of the normal base-flow depletion curve and frequency curves of runoff from concurrent precipitation and snow melt. Base flow from antecedent precipitation, together with runoff from concurrent precipitation and snow melt, constitutes the total runoff. The base flow resulting from antecedent precipitation may be projected several weeks or, in some cases, months into the future. The added runoff from subsequent precipitation may be evaluated by a frequency curve of such runoff component from past records. If the latter component is not great in relation to base flow, reliable forecasts of total flow are possible. The method is illustrated by application to two streams in the Columbia River basin where conditions are favorable to its use.

Introduction--Reliable forecasts of stream flow are becoming increasingly necessary for the efficient operation of projects utilizing surface water. Hydrologists and engineers have given a great deal of attention to the problem of forecasting flood peaks and flood volumes, and successful methods have been developed for making such forecasts from snow survey and precipitation data. Forecasting discharge during low-flow periods has received less attention, probably because river discharge during such periods has been of minor importance in project operation. However, the operation of modern integrated power systems, irrigation projects developed to the full capacity of the water supply, and other water projects having limited storage facilities depends to a great extent upon the low flows, the occurrence of which may coincide with periods of great demand.

Little progress has been made toward developing a sound procedure for determining probable future flow during low-flow periods because one component of that flow is associated with concurrent precipitation or snow melt or both, which at present can not be predicted more than a few days in advance. There are some streams, however, for which base flow resulting from antecedent precipitation forms the major portion of stream flow for periods of one to three months. Under such conditions, base flow may be forecast for like periods. MERRIAM [1948] used an index based on elevations of water surfaces in wells to estimate base flow of Susquehanna River seven and 14 days in advance. The method presented in this paper is readily applicable to longer periods and utilizes base-flow depletion curves. The other component of stream flow, resulting from concurrent precipitation and snow melt, then may be evaluated from a frequency curve of such component based on past records, using any convenient unit of time, preferably a month or a multiple thereof. Thus the forecaster has a means of determining the probability of runoff within a relatively narrow range. This method is illustrated by application to the flow of Clark Fork at St. Regis, Montana, during winter, and to Slocan River near Crescent Valley, British Columbia, during late summer.

The base-flow depletion curve--The analysis of the hydrograph given in the Hydrology Handbook [AMERICAN SOCIETY OF CIVIL ENGINEERS, 1949, pp. 70-71] describes the origin of the base-flow component of stream flow. It has been recognized for many years that base flow of a stream at a particular point diminishes at a characteristic rate until supplemented by precipitation or melting snow. This rate is defined by the base-flow depletion curve, which is usually derived graphically as explained by SNYDER [1939]. Figure 1 shows the base-flow depletion curves for Clark Fork at St. Regis, Montana, one for summer and one for winter.

The following description of Clark Fork basin is requisite to recognition of the various factors influencing depletion of base flow. Clark Fork basin above St. Regis lies west of the Continental Divide and east and north of the Bitterroot Range. Within its 10,500 sq mi area, altitudes range from about 2600 ft to over 8000 ft above sea level. Winter precipitation occurs predominantly as snow and does not produce substantial runoff until the following spring, except at the lower altitudes where some winter melting occurs. Many diversions for irrigation are made from tributaries but the total diversion probably does not appreciably affect the natural stream regimen, certainly not during the autumn and winter. A typical hydrograph showing the spring snow-melt period followed by a period of diminishing flow until the next spring is given in Figure 2. Direct runoff from precipitation and winter snow melt is usually small. Extreme cold often reduces the

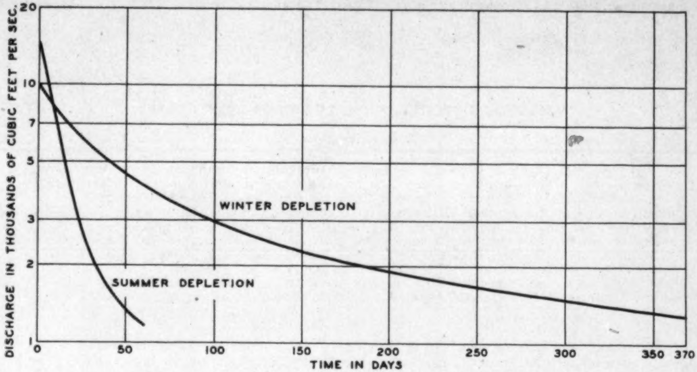

Fig. 1--Base-flow depletion curves for Clark Fork at St. Regis, Montana

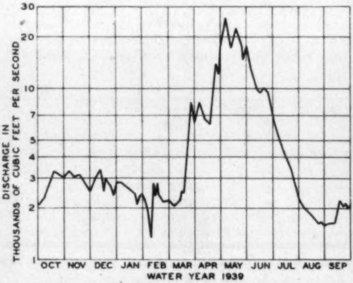

Fig. 2--Typical hydrograph for Clark Fork at St. Regis, Montana

flow substantially for short periods during the winter.

The difference between base-flow depletion rates for summer and for winter is related to diversities in topography, geology, temperature, and precipitation. The rapid diminution of summer base flow presumably results from draining of ground water from the high-altitude zones in the basin, such areas having been heavily recharged during the spring snow melt while the lower altitudes had no substantial recharge. Under these conditions the dominant portion of base flow is derived from the higher altitudes; consequently, base flow will decrease more rapidly than it would if the whole basin were uniformly recharged. This marked difference between summer and winter depletion rates is characteristic of many streams in the Columbia River basin. Base-flow depletion for many other streams in the same basin may be represented by a single curve for each, applicable throughout the year. Each of this latter group differs widely in certain basin characteristics from those in the former group. Evapotranspiration changes during the year have been found to change the depletion rates in some parts of the United States. A study of over 30 streams in Columbia River basin has failed to show changes in the base-flow depletion rate definitely attributable to this cause, probably because the influence of other factors predominates.

Forecasting base flow--If base flow constitutes the entire flow of the stream at the time of forecast, the hydrograph of daily discharge is extended by means of the depletion curve to the desired future time. More commonly, the discharge at the time of forecast differs from base flow. It may be larger owing to a direct-flow component or smaller as a result of ice formation and consequent impounding of water in the channels during extremely cold weather. Assuming the discharge at the time of forecast is greater than base flow, the procedure of forecasting base flow entails: (1) determining base flow prior to the latest rise in discharge, (2) estimating the increase in base flow resulting from the precipitation or snow melt which caused the rise (by the method described subsequently), (3) adding this increase to base flow preceding the rise, and (4) projecting the depletion curve from the discharge obtained in the third step to the desired future date.

The increase in base flow resulting from precipitation or snow melt, or both, may be computed from the hydrograph of the rise by relating increase in base flow to height of the rise above beginning base flow and to beginning base flow. The number of days from the beginning of the rise to the peak has little relation to the base-flow increase, probably because the length of rise is related to the height of rise and because the range in length of rise is short.

The increase in base flow occurring at the time of an increase in stream flow may be expressed by

$$X_1 = 0.00184\, X_2^{0.713}\, X_3^{0.943} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

applicable to rises on Clark Fork at St. Regis from October through March. The variables in this equation are illustrated in Figure 3. The dependent variable, X_1, is the increase in base flow (in cubic feet per second) resulting from the factor which caused the rise and is measured on the day of the peak from the base-flow depletion curve projected from base flow prior to the rise. Similarly, X_2 is the number of cubic feet per second from the same point on the depletion curve to the mean peak (average of three highest daily mean discharges), and X_3 is the base flow from which the first two variables were measured. This equation applies only to rises from precipitation or snow melt, or both, not to those resulting from release of water or ice stored in the channel. Furthermore, it defines only the increase in base flow that will occur if the stream recedes normally from the rise; for when precipitation or snow melt, or both, occurs after the peak an additional increase in base flow may result.

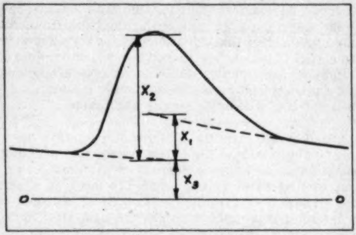

Fig. 3--Storm hydrograph showing the increase in base flow and the variables used to compute that increase

Equation (1), based on data for 19 rises during the period 1918-51, was derived statistically by correlating the logarithms of the actual values of the variables. The resulting adjusted coefficient of multiple correlation is 0.95 and the adjusted standard error of estimate (transformed from logarithms to actual discharge) is 31 pct above and 24 pct below the mean. Figure 4 compares the actual values of base-flow increase with those computed by the equation.

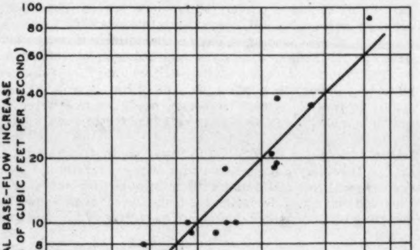

Fig. 4--Comparison of actual and computed base-flow increases for Clark Fork at St. Regis

The increase in base flow resulting from several peaks in close succession may be obtained by repeated application of (1), using the first computed increase as the basis for computation of the second, and so forth. Compound peaks may be treated similarly or, if they are not more than a week apart and the trough between them is minor in relation to the total rise above base flow, they may be considered as a single rise which reaches a peak slightly greater than the higher of the compound peaks and at a time midway between them. In the event that further runoff generation occurs other than as well-defined rises, base flow after the termination of such runoff generation may be discriminated by so placing the depletion curve on the hydrograph that the hydrograph can be logically extended (as regards slope) through a transition to the depletion curve.

Available hydrographs for a stream usually include few rises which begin from base flow and recede to base flow. Therefore, much of the base data for development of a relation between base-flow increase and characteristics of the rise must be abstracted from hydrographs of rises that begin above base flow and are closely followed by another rise. Under these circumstances, both beginning and ending base flow must be estimated. Although the use of such data in a correlation results in a rather large standard error of estimate, the uncertainties in the base-flow data tend to be compensating. This premise is supported by the fact that equations based on such data have given reasonable results whenever applied to actual rises on the stream for which each was derived. Data should be abstracted from enough rises so that each variable is defined throughout its probable range. In addition, data for both rapid and slow rises, and those having fluctuations in the rising limb should be used so that the defined relation will be generally applicable.

Forecasting by the method presented here is based on the premise that the stream-flow hydrograph will not fall below the depletion curve and, therefore, that the curve represents minimum possible flow under all natural conditions. An exception occurs during periods of extreme cold when ice is forming in the stream channels and impounding water behind small ice jams, in which case the water retained in channel storage reduces stream discharge below base flow. As soon as the period of rapid formation of ice is ended, stream discharge quickly returns to base flow; subsequently, the release of small ice jams will increase the discharge above base flow until nearly all the withheld water has been recovered. Therefore, during winter the depletion curve will not always indicate the minimum possible discharge for short periods. However, over periods of several weeks or more the depletion curve will average these temperature fluctuations and is therefore applicable. The estimate of base flow during a "freeze-up" is made by projecting the depletion curve from base flow before the cold period began, and the forecast requires only further projection. Discrimination of base flow during winter requires recognition of the effects of temperature in producing direct flow and in temporarily reducing stream flow. Judgment based on a knowledge of the particular stream is an important factor.

By methods described in the preceding paragraphs, base flow can be determined through the period of forecast. The volume of runoff during the forecast period (represented by the area under the depletion curve) may be more useful in certain situations. To this end, a storage curve or a table showing the volume corresponding to each of the values of daily discharge from the base-flow depletion curve can be made by cumulating the successive daily discharges from the lower end of the curve. The volume of base flow that will occur in the time required for base flow to decrease from a higher to a lower discharge equals the difference in the volumes corresponding to those discharges. Table 1 gives the winter base-flow depletion characteristics of Clark Fork at St. Regis. In order to be usable, the table should be expanded to show values for each day.

The discharge of some streams in the Columbia River basin at certain times of the year is predominantly base flow. A forecast of base flow under these conditions, therefore, constitutes a reasonable forecast of the total flow. It defines the minimum flow except during short periods of unusually cold weather and any other deviation from the forecast is known to be positive. However, the majority of streams have considerable runoff resulting from precipitation or snow melt during a period of forecast.

Estimating runoff from concurrent precipitation and snow melt--This component of stream flow can not be forecast because weather conditions are not determinable more than a few days in advance. However, the most probable value of this component may be obtained from a frequency curve of runoff in excess of that derived from ground water in storage at the beginning of the period of forecast. Figure 5 shows such frequency curves for Clark Fork at St. Regis for each month from November through February. The runoff shown by these curves is not all direct flow; some increases in base flow usually result from the precipitation or snow melt occurring during the month. Neither does the discharge represent all the runoff resulting from precipitation or snow melt during the month; some will occur as base flow in the following month or months. Furthermore, some direct runoff from a storm late in the month may occur in the following month.

Table 1--Base-flow depletion characteristics of Clark Fork at St. Regis, Montana, October - March

Day	Discharge	Volume
	cfs	cfs days
1	10,000	1,000,405
5	9,100	961,755
10	8,200	918,055
20	6,800	842,855
30	5,800	779,355
40	5,100	724,755
50	4,500	676,455
70	3,660	594,935
90	3,110	527,285
120	2,620	441,615
150	2,290	368,025
180	2,020	303,440
210	1,840	245,650
250	1,670	175,515
290	1,510	111,835
330	1,380	54,120
370	1,260	1,260

Estimates of runoff from precipitation or snow melt during the period of forecast are dependent upon the frequency selected. Although this selection may be largely arbitrary, the estimator will be influenced by the purpose for which the forecast is made. The frequency curve shows the range of past experience and makes possible forecasts of limiting values such as the minimum probable and most probable. When this component is a small portion of the total stream flow, uncertainties in its estimation influence the total estimated flow only moderately. In contrast, a frequency curve of total runoff would show a much larger range of discharge and, consequently, estimates made from it would be much less reliable.

Forecasting the flow of Clark Fork at St. Regis, Montana--The method of forecasting described in the foregoing paragraphs has been applied to records for Clark Fork at St. Regis for water years 1930-1948. Assuming that the necessary curves were defined prior to 1930, forecasts by this method are plotted against measured runoff for each of the months November to February, inclusive, in Figure 6. A similar degree of accuracy could be shown for October. The forecasts shown are (1) the assured flows from base-flow depletion curves and (2) those obtained by adding to the assured flow the estimated runoff from concurrent precipi-

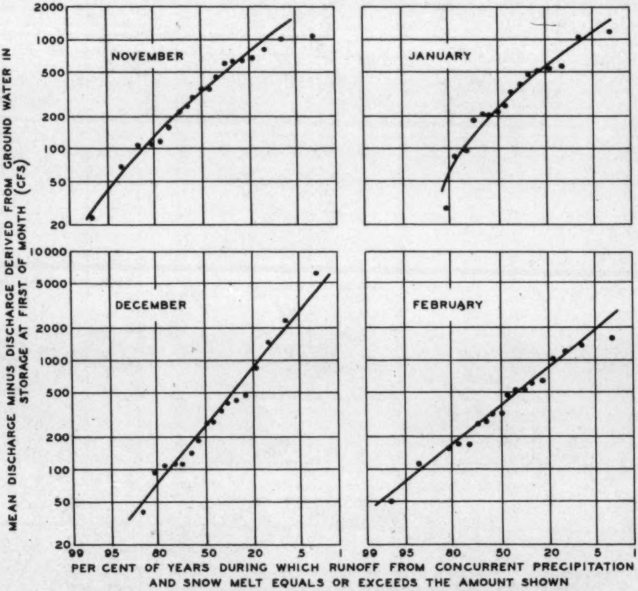

Fig. 5--Frequency curves of runoff in excess of that derived from ground water in storage at first of month, for Clark Fork at St. Regis, Montana, 1930-48

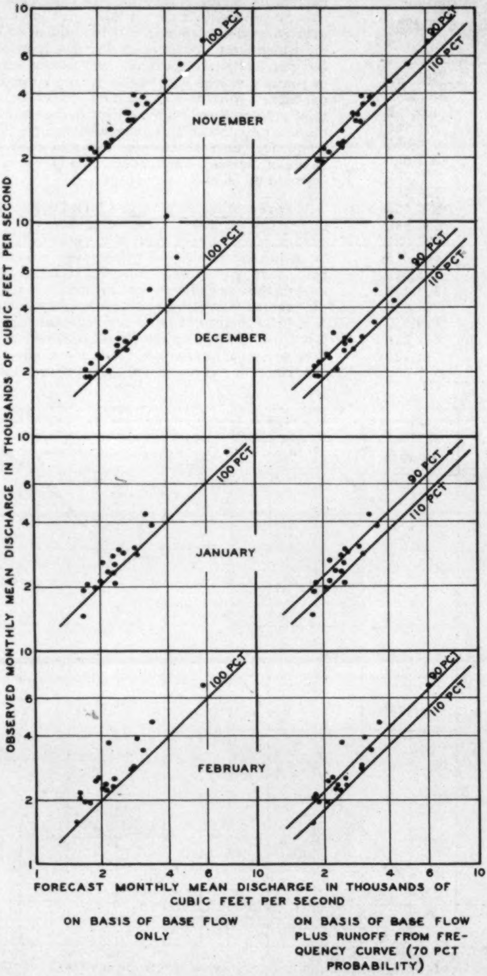

Fig. 6--Evaluation of the forecasting method as applied to Clark Fork at St. Regis, Montana, 1930-48 tation and snow melt determined from frequency curves using a 70 pct probability. The percentage lines of Figure 6 define the locations at which forecast flow would be the labelled percentage of observed flow. Those forecasts which include estimated runoff from concurrent precipitation and snow melt are considerably better than those of assured flow alone.

Several forecasts of assured flow during December and January are greater than the measured runoff owing to prolonged periods of extreme cold. Had the period of forecast been longer, the water temporarily held in channel storage would have been released and , consequently, total runoff for the period would have equalled or exceeded that determined from the base-flow depletion curve. Referring to the left-hand curve for January (Fig. 6), the three points which plot to the right of the 100 pct line are for the years 1930, 1937, and 1942. On the corresponding February curve, points for each of these years plot to the left of that line. Because January discharge is less than base flow, the base flow on February 1 would indicate no recharge over January 1 conditions. Therefore, the combined runoff for January and February should equal or exceed the sum of the assured flows for those months if recovery of the January base-flow deficiency occurs in February. The data for the three above-mentioned years also are in accord with this latter requirement.

It is not strictly correct to use records for the period 1930-48 to evaluate the forecasting procedure because both the base-flow depletion curves and the frequency curves were developed from data for that period. Furthermore, the estimates of base flow at the first of each month were made with the hydrograph completed through the period of forecast rather than only to the beginning of that period. Under actual forecast conditions the estimate of base flow at the beginning of the forecast period sometimes will be less accurate than one determined after the actual runoff for the period is available. In general, this loss in accuracy would be five per cent or less if graphs of temperature and precipitation were used in interpreting the fluctuations in the hydrograph and if increases in base flow were computed by equation where applicable. In spite of these noted limitations, actual forecasts of monthly runoff of Clark Fork at St. Regis should differ only nominally from those shown in Figure 6.

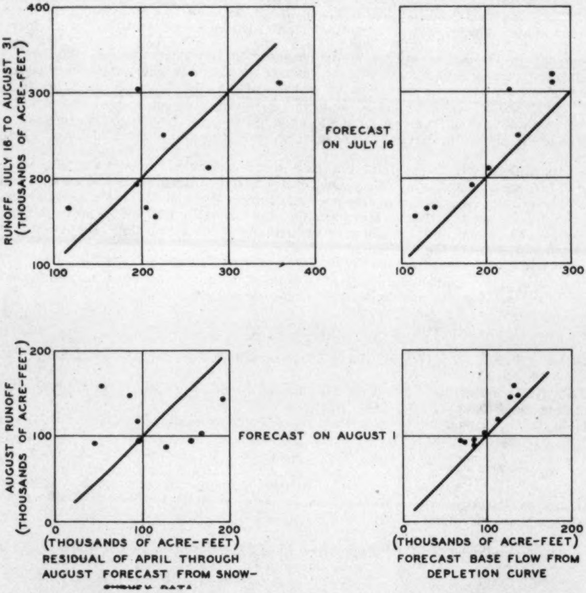

Fig. 7--Comparison of late-summer runoff forecasts based on spring snow surveys and on the base-flow depletion curve, Slocan River near Crescent Valley, British Columbia, 1938-46

Application of depletion curves during summer--Forecasts of the winter flow of Clark Fork are useful primarily in planning reservoir operation for power generation. Another use of the depletion-curve method of forecasting, with wide application throughout western United States, would provide forecasts of the assured flow during late summer which would supplement the forecasts made in spring from snow survey or precipitation data. This type of forecast provides information that may be useful in planning operations involving storage and in the equitable distribution of water for irrigation.

Forecasts of the total volume of runoff during the snow-melt period in spring and summer are made for many western streams by correlation with snow survey and precipitation data. As the season progresses, the residual of such a forecast diminishes in accuracy. The residual is defined as the total forecast minus that which has occurred up to an indicated date. Toward the latter part of the forecast period when the greater part of the spring runoff has occurred, the error of the forecast residual becomes so great that the forecast is no longer useful. In many streams the forecast has served its purpose by this time, but in others accurate forecasts of late summer flow are needed, particularly if water requirements are great in relation to the discharge.

MacLEAN [1948] found a good correlation between total volume of runoff April through August and the water content of the snow on April 1 adjusted for the previous autumn precipitation for Slocan River near Crescent Valley, British Columbia. For the years 1938-46, all points plotted within seven per cent (four were within three per cent) of the regression line. Residuals of forecasts based on this better-than-average correlation are shown for the period July 16 to August 31 and for the month of August in Figure 7. The corresponding forecasts of assured flow, obtained from base flow at the first of each period projected along the depletion curve to the end of the period are shown on the right side of Figure 7. The base-flow depletion-curve method is not applicable until the cessation of direct flow from snow melt. The time of this cessation varies from year to year but was never found later than mid-July for Slocan River. Figure 7 illustrates the advantage as early as mid-July of the depletion-curve method as a supplement to forecasts based on spring snow surveys. For August the depletion-curve method gives very good results. The runoff from concurrent precipitation in Slocan River basin was not included in the forecast because this factor is quite small. However, its inclusion might increase the utility of the forecasts.

Conclusion--The method of forecasting presented in this paper is applicable to all essentially unregulated streams. Best results will be obtained for streams where the runoff includes considerable ground-water effluent and for those seasons when runoff from precipitation or snow melt, or both, constitutes a small portion of the total. Forecasts are not limited to a month but may be made for periods ranging from a few days to as long as several months in some cases. A further advantage of the method is that only antecedent stream-flow and weather records are required.

Lack of well records in the Columbia River basin precludes comparison with Merriam's method of forecasting base flow from ground-water levels. However, based on experience in developing depletion curves for many streams in Columbia River basin, the depletion-curve method appears to give as good results as Merriam's, is less complicated, and is more flexible as regards period of forecast. The inclusion of an estimate of the direct flow component further increases the reliability of the forecast.

Acknowledgment--The author wishes to express his appreciation to C. C. McDonald for his guidance in the development and application of the method presented.

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RELATIONSHIP OF THE MINERAL CONSTITUENTS IN SOLUTION TO STREAM FLOW, SALINE RIVER NEAR RUSSELL, KANSAS

Walton H. Durum

Abstract--Studies were made of the salinity relationships of ground-water inflow in the Saline River basin, Kansas, during the period 1945-49 in connection with the program of the Interior Department for development of the Missouri River basin. Mineralization in the Saline River near Russell, Kansas, fluctuates rapidly from more than 4400 ppm in low water stages to approximately 200 ppm at flood stage. Hydrographs for the 1947 and 1948 water years reveal that surface runoff comprised approximately 65 pct of the total runoff for each year and carried an estimated 24 pct of the annual dissolved solids discharge. The dissolved minerals in surface runoff were derived from surface contact and channel scour. In contrast, runoff from ground-water sources contributed 35 pct of the total runoff and 76 pct of the annual dissolved solids discharge.

Ground water discharging to the Saline River and its tributaries carries strong concentrations of dissolved minerals that are leached from saliferous and gypsiferous shales and sands of the consolidated materials. Sodium, chloride, and sulfate are the most prominent constituents. Chloride concentrations of more than 1900 ppm were identified with low flow and the chloride ion is related hyperbolically to stream flow. Equations were developed by the least-squares principle to correlate between specific conductance of the water and several mineral constituents in solution.

Introduction--Data relating to the quality of surface water of the United States have been published annually since 1941 in Water Supply Papers of the U. S. Geological Survey. Studies of these data for some streams as in the southwestern United States [HEM, 1948] show that the concentration of dissolved solids fluctuates widely as the stream discharge changes. Other investigators [FEDERAL SECURITY AGENCY, 1949] have noted the correlation of specific ion concentrations with stream flow. The character patterns of ground and surface waters [HORBERG, SUTER, and LARSON, 1950] have been used in determining infiltration of river water into water-bearing gravels.

Numerous chemical relationships that exist in streams through various stages of flow are presented in the literature; however, detailed quantitative measurements of the mineral substances contributed to a stream by ground-water inflow and surface runoff have not been reported. These relations are developed briefly in this study. Certain assumptions were necessary, and it was recognized that the results obtained are applicable only to this location or to those basins where the equivalent geologic and hydrologic relations exist.

Data presented herein represent analyses of samples collected daily from the Saline River near Russell, Kansas, during the period 1945 to 1949. After determination of specific conductance, the samples were composited by one of two methods. Prior to 1948 the composites consisted of equal quantities of water for a ten-day period, whereas later samples were composited in proportion to stream discharge. Generally the samples obtained at peak flows were analyzed individually. The data were tabulated according to the Geological Survey water year, which consists of the 12-month period October to September. The term specific conductance (micromhos at 25°C) is used throughout the text and the illustrative material. Specific conductance is a measure of the total ionizable solids in the water and is widely used in quality-of-water investigations for approximating the quantity of dissolved mineral matter in the water.

Relation of chloride to stream discharge--Examination of the analyzed data at the Russell station revealed an inverse relationship of stream discharge and the mineralization in the water, particularly with respect to the chloride ion. All chloride values in parts per million obtained during the period October 16, 1945, to October 1, 1949, were plotted with corresponding stream discharge in cubic feet per second. The curve (see Fig. 1) was fitted by the method of averages, which required replotting the data on logarithmic paper and fitting a straight line to the plotted points. A correlation index of 0.94 was obtained. The average curve approximated a hyperbolic relationship that can be expressed

$$Cl \times Q = K$$

where Cl = chloride in parts per million
Q = stream discharge in cubic feet per second
K = constant

An average value of 34,500 was obtained for the constant (K). At any point on the calculated K-curve (see Fig. 1), the chloride discharge is equal to about 2.1 pounds of chloride per second or about 93 tons of chloride per day. At flows less than 25 cfs, which discharge peak loads of chloride, wide scatter of the plotted points occurs. Inversely, during high stream runoff (above 1000 cfs), the chloride concentration approaches zero and the values of K show wide variation. The variation is particularly noticeable during initial spring runoff when rapid rise in stage is accompanied initially by rapid increase in mineral content. Most of the increase is probably related to solution of soluble materials in the channel scour and to salts deposited by evaporation at low flow.

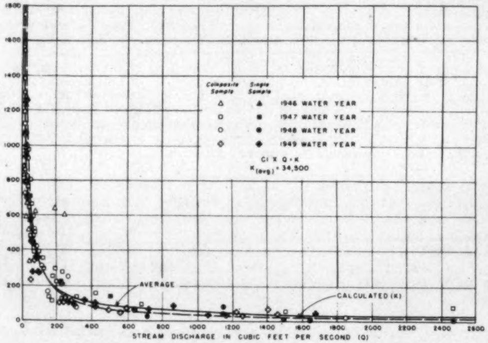

Fig. 1--Relation of chloride to stream discharge

Obviously, the statistical treatment of data comprised of average stream flow and composite analyses values cannot be expected to yield more than the suggestive or the approximate. However, the positions of the two curves with respect to the plotted points, together with the good correlation index obtained for the average curve, are indicative of the existing discharge-chloride relationship.

To compare the value of K obtained with actual field data, chloride concentrations in the Saline River at the Russell station for comparable stream discharges were tabulated in Table 1. The data show rather good agreement with the chloride discharge of 2.1 lb per sec as calculated from the K-curve.

Table 1--Comparison of chloride discharges at selected comparable stream flow

Date	Mean discharge	Chloride concentration		Chloride discharge	
	(cfs)	ppm	tons/ac ft	lb/sec	tons/day
Feb. 1-10, 1947	54	800	1.09	2.7	117
Mar. 1-10, 1947	52	696	0.95	2.3	97.7
Apr. 1-5, 1947	53	576	0.78	1.9	82.4
Apr. 25, 1947	51	700	0.95	2.2	96.4
Mar. 1-31, 1948	51	480	0.65	1.5	66.1
Calculated from K (Fig. 1)	52	663	0.90	2.1	93.2

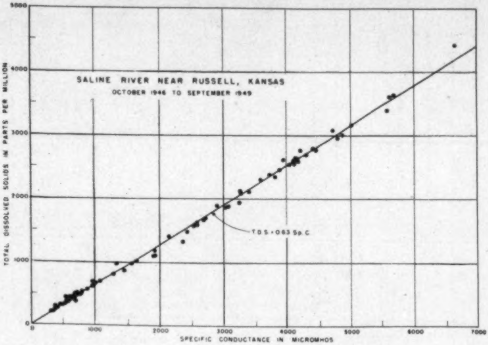

Fig. 2--Relation of dissolved solids to specific conductance of water

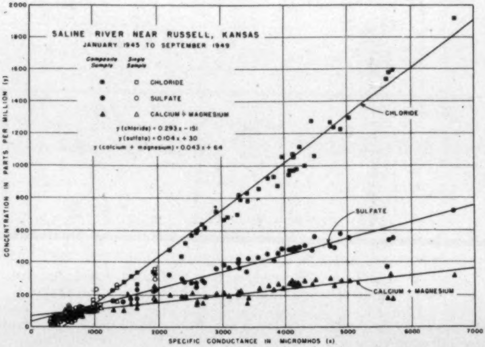

Fig. 3--Relation of mineral constituents to specific conductance of water

Relation of several constituents to total mineralization expressed as specific conductance--The relationship of dissolved solids to specific conductance is plotted in Figure 2 for three water years at Russell. The linear relationship that exists in the plotted data indicates that the approximate ratio of dissolved solids to specific conductance is 0.63. The relationship of various ions in solution to specific conductance is shown in Figure 3. Chloride, sulfate, and calcium plus magnesium in analyses principally for the 1946, 1948, and 1949 water years are plotted with specific conductance in micromhos. A linear relationship is found to exist in each of the three groups of data and can be represented by

$$y = a + bx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where y = concentration in parts per million
$a + b$ = constants
x = specific conductance in micromhos

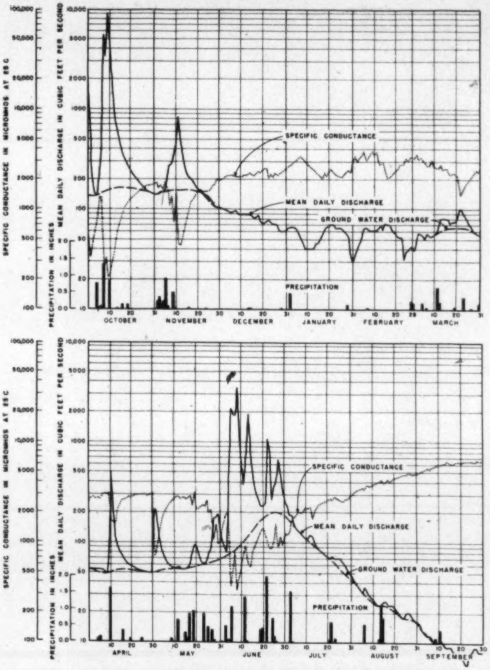

Fig. 4--Relation of specific conductance to ground-water discharge and mean daily runoff, October 1946 to September 1947

By using (1) and applying the least-squares principle, the arbitrary constants, a and b, were found to have the following values:

	a	b
chloride	-151	0.293
sulfate	+30	0.104
calcium + magnesium	+64	0.043

Thus by substitution in (1)

$y(Cl)$ = Sp. cond. in micromhos × 0.293 - 151
$y(SO_4)$ = Sp. cond. in micromhos × 0.104 + 30
$y(Ca + Mg)$ = Sp. cond. in micromhos × 0.043 + 64

For conductance values of less than 500 micromhos, which represent mineral content at peak flows, the linear relationship, particularly for chloride and sulfate, declines somewhat. This would be expected in view of the transition from a sodium chloride and sodium sulfate type water at low discharge to a calcium bicarbonate type water at peak flows.

The curve for the bicarbonate ion (not shown) shows less slope than that in the calcium and magnesium relationship and indicates greater uniformity of the bicarbonate concentration over

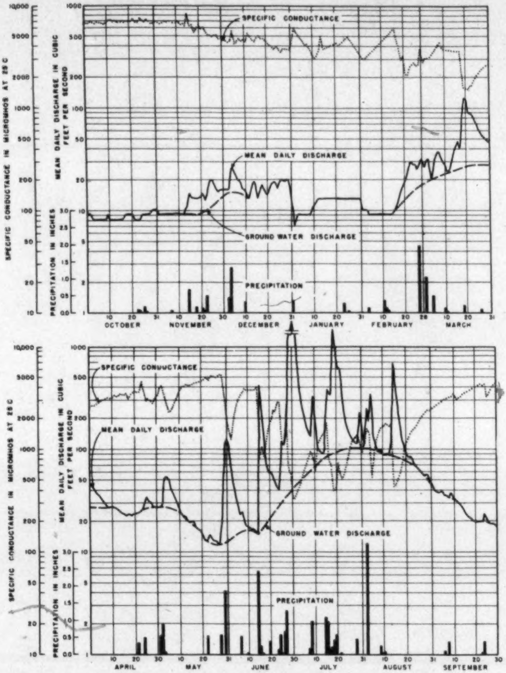

Fig. 5--Relation of specific conductance to ground-water discharge and mean daily runoff, October 1947 to September 1948

wide range in stream flow. These relationships give indication that mineral substances in solution are brought into the Saline River at the Russell station from natural sources and in approximately proportional quantities of the individual ions.

A more exacting study of the discharge-ion relationship involves an evaluation of data for concentrations less than approximately 500 micromhos and for data representing concentrations greater than 500 micromhos. However, the derivation of two sets of curves has no particular value in this study except to appraise factors other than base-flow dilution that enters into mineralization of surface runoff.

Ground-water dissolved solids load and discharge--An estimate was made of the quantity of ground water and its dissolved mineral load, which percolates into the Saline River above and is discharged at Russell. The general method applied to compute ground-water runoff is a modification of that used by HOUK [1921] in his investigations of flood control in Ohio. It is based on the assumption that the surface runoff for any rain is carried out of the immediate area within a few days from the time it falls. It is further assumed that during fair weather and during winter months of continuous below-freezing temperatures, the water discharged by the Saline River is nearly all ground water. The daily precipitation at Russell for October 1946 to September 1947

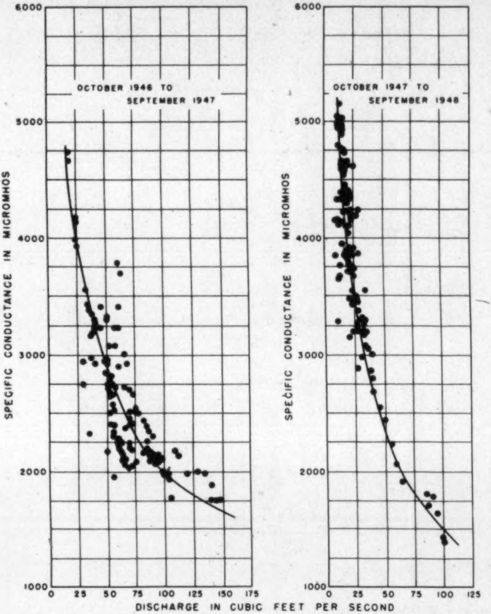

Fig. 6--Relation of specific conductance to ground-water discharge

and for October 1947 to September 1948 is shown diagrammatically in Figures 4 and 5. The graph indicates a rather uneven distribution of precipitation during the year; most of the rain falls in the summer months from May to September. Mean daily below-freezing temperatures occur in December, January, February, and usually in the first days of March. However, during any of these months, days of alternate freezing and thawing may be reflected to some extent by increase in runoff at the Russell station.

The mean daily stream discharge in cubic feet per second at Russell is also shown in Figures 4 and 5. In general, peak runoff occurs in early summer months coincident with heavy rainfall and in winter months following days of high temperatures and rapid thaws. Low runoff occurs during the fall and winter months.

The somewhat arbitrary method of connecting the troughs or low points of the mean daily discharge hydrograph was used in the ground-water runoff curve. As pointed out by MEINZER [1928, p. 111], "There is uncertainty as to the amount of ground-water runoff during the flood stage of a stream, and the longer the stream is kept at an abnormal stage by successive rains at short intervals, the greater becomes the uncertainty. During the flood stage, the discharge of ground water is probably checked because the water levels of the streams are likely to be higher than the adjacent water table. However, periods of flood runoff are commonly also periods of ground-water recharge when the water table is built up. Hence the discharge of ground water is usually greater after a flood stage than it was before the flood."

In accordance with Meinzer's views, the ground-water curve was raised slightly during flood stage to meet the recession curve of total runoff. Little precipitation occurs in December, January, and February, and the ground-water curve would be expected to approach or be equal to the total runoff curve.

Mean daily ground-water runoff was read from the hydrograph and totaled for the 1947 and 1948 water years. The computation of dissolved solids discharge in the total runoff involved averaging specific conductance for each year by weighting the specific conductance of daily samples with stream discharge. It was previously established that a linear relationship of specific conductance and dissolved solids exists at the Russell station from which a weighted average for dissolved solids can be readily computed as follows:

$$\text{Sp. cond. (micromhos)} \times 0.63 = \text{dissolved solids (ppm)}$$

The computation of the dissolved solids discharge in ground-water runoff is more indirect and is based on the supposition that the concentration of mineral substances in ground water adjacent to the stream fluctuates with changes in ground-water levels. Daily specific conductances for the total runoff and ground-water runoff are identical for those days on which the curves coincide; however, it was necessary to determine conductance values for ground-water discharge on noncoincident days. To obtain these data, the specific conductance for known ground-water runoff was plotted, and a curve fitted to the plotted points, as shown in Figure 6. Estimated daily specific conductance values for the remaining mean daily ground-water discharges were read from the curve, and a weighted specific conductance for each of the two years were determined as before. A summary of the calculated dissolved minerals discharge for the 1947 and 1948 water years is given in Table 2.

Table 2--Summary of hydrograph study, water years 1947 and 1948

Year	Water discharge		Total	Percent of total		Dissolved solids				Total discharge				Percent dissolved solids discharge	
						Analysis[a]	Calculated[b]			Analysis	Calculated				
	Surface	Ground		Surface	Ground		Total	Surface	Ground		Total	Surface	Ground	Surface	Ground
	ac ft	ac ft	ac ft	pct	pct	$\frac{\text{tons}}{\text{ac ft}}$	$\frac{\text{tons}}{\text{ac ft}}$	$\frac{\text{tons}}{\text{ac ft}}$	$\frac{\text{tons}}{\text{ac ft}}$	ton	ton	ton	ton	pct	pct
1947	102,635	54,080	156,715	65	35	0.96	0.82	0.29	1.80	150,450	128,510	31,170	97,340	24	76
1948	36,494	20,582	57,076	64	36	1.23	1.15	0.42	2.44	70,200	65,640	15,420	50,220	24	76

[a] From weighted average analyses of samples composited by stream discharge or 10-day equal quantity.
[b] From weighted average of specific conductance of daily samples (prior to compositing).

Results obtained by weighted averages of laboratory analyses of dissolved solids are tabulated for comparison. The differences in terms of total dissolved minerals discharge are about 22,000 tons for 1947 and 4600 tons for 1948.

Several important relationships are indicated by the data in Table 2. Most significant, perhaps, is that surface runoff in the Saline River, although functioning in part as a diluent agent for the ground-water increment, carries a significant dissolved mineral load of approximately 0.40 ton per ac ft (310 ppm) at low flows exclusive of the ground-water increment, and about 0.30 ton per ac ft (220 ppm) in periods of high runoff (see Table 2). Most of the dissolved minerals are brought in by ground water, which contributed 76 pct of the annual dissolved solids load for both years.

Dissolved solids loads in ground-water inflow and surface runoff vary inversely with flow; however, the relationship is not proportional. The summary in Table 2 shows that the total water discharge in 1947 was nearly three times greater than that discharged in 1948. Dissolved solids loads for the two periods, however, differ by only about one-third (0.82 and 1.15 tons per ac ft).

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GEOCHEMICAL RELATIONSHIPS OF WATER IN THE POWDER RIVER BASIN, WYOMING AND MONTANA

Herbert A. Swenson

Abstract--Geologic factors largely determine the composition and the amounts of dissolved solids that are transported by the Powder River and its tributaries. The chemical character of the water in the basin differs widely from one stream to another and is variable in each stream from headwaters to mouth. Mountainous areas underlain by igneous rocks of Precambrian age contribute small quantities of soluble materials to the river system; the concentration of mineral solids may be less than 50 ppm. Streams heading in upland country and draining a region that is largely underlain by Tertiary sandstones and shales transport salts in concentrations exceeding 2000 ppm. The composition of mineral substance in the river water can be correlated with occurrence in the area of such rocks as granite, limestone, gypsum, and shale.

Introduction--In 1946 the U. S. Geological Survey began an investigation of fluvial sediments and chemical quality of the water in the Powder River basin, Wyoming and Montana. This program, which is continuing, relates to the overall plan for development of irrigation and hydroelectric power, and regulation of floodwaters in the basin. This paper presents data showing certain relationships between the chemical character of the water and the geology of the region.

Description of basin--The Powder River and its tributaries drain an area of about 13,400 sq mi in northeastern Wyoming and southeastern Montana. From its headwaters to its confluence with the Yellowstone River east of Miles City, Montana, the Powder River (including the South Fork) is about 480 mi long. The principal tributaries are Crazy Woman Creek, Clear Creek, the Little Powder River, and Mizpah Creek. Figure 1 is a map of the basin.

The average annual discharge of the Powder River at Arvada, Wyoming, is about 425 cfs; downstream near the mouth in the vicinity of Locate, Montana, the average annual discharge is approximately 800 cfs. Maximum discharges at the Arvada station have exceeded 70,000 cfs. Flow above this station is partly diverted for irrigation.

The topography of the Powder River basin ranges from rugged mountains to semi-arid plains. Mountains, plateaus, uplands, lowlands, badlands, and river terraces form the varied landscape of the basin. The drainage basin is bounded on the southwest by the Bighorn Mountains. Remaining boundaries are formed by low divides that separate the Powder River basin from the basins of the Tongue, Little Missouri, Belle Fourche, Cheyenne, North Platte, and Bighorn Rivers. Land forms of the basin are shown in Figure 2.

Wide local differences in temperature and precipitation exist. Heavy precipitation exceeding 30 inches, most of which is snow, occurs in the high mountains. In the semi-arid plains section the average precipitation is less than 15 inches.

General geology of area--Rocks exposed in the Powder River basin are granites and schists of Precambrian age and a thick series of sedimentary strata that range in age from Cambrian to Recent [HEMBREE and Others, 1952]. Outcrops of rocks older than Mesozoic are confined to areas in or near the mountains. Rocks of Precambrian age are igneous and metamorphic and erode slowly. The Paleozoic rocks, mostly limestones and sandstones, but including shales and dolomites, are relatively resistant to erosion.

Rocks of Mesozoic age crop out chiefly along the east flank of the Bighorn Mountains and over large areas in the southwest part of the basin. Sedimentary rocks of the Mesozoic era differ in erosive properties. Rocks of this age are limestones, sandstones, shales, siltstones, and gypsum. Rocks of Cenozoic age cover the greater part of the plains section of the basin north of Sussex. Those of Paleocene and Eocene age consist of sandstone, shale, siltstone, and some coal. Erosion appears to be at a moderate rate. Small patches of rocks younger than Eocene and older than Recent alluvial deposits occur in and adjacent to the mountains.

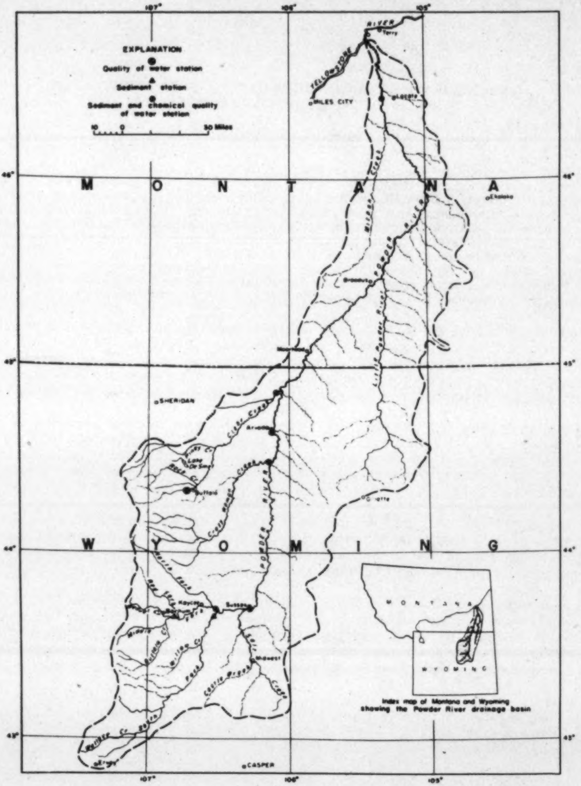
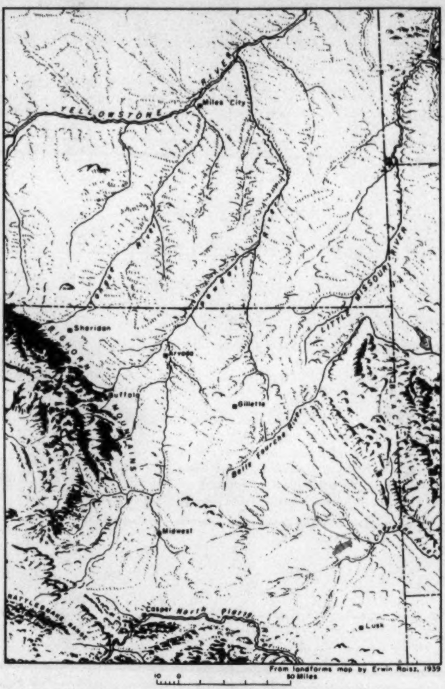

EXPLANATION
Quality of water station
Sediment station
Sediment and chemical quality of water station
10 0 30 Miles
107°
106°
105°
46°
45°
44°
43°
M O N T A N A
W Y O M I N G
YELLOWSTONE RIVER
MILES CITY
SHERIDAN
CASPER
POWDER RIVER
Little Powder River
Clear Creek
Crazy Woman Creek
Index map of Montana and Wyoming showing the Powder River drainage basin
MONTANA
WYOMING

Fig. 1--Map of Powder River drainage basin, Wyoming and Montana

Geochemistry of natural water--As PALMER [1911] has pointed out, the chemical character of a river water is largely determined by the geological formations that the river traverses. Rivers carry the weathering products as ions or as colloids. The amount of these products varies both with climate and with the chemical and physical properties of the rocks and soils in the catchment area. Practically all the minerals that make up the rocks in the Earth's crust are soluble in water to some extent, particularly in water containing dissolved carbon dioxide. In a paper by HEM [1950] the author stresses the fact that the action of water in attacking minerals, leaching out soluble products, and leaving insoluble residues behind is a very important process in erosion and the disintegration of rocks into soil.

Geochemical relationships of basin water--In the foregoing discussion the importance of the properties and composition of the rock formations as determinative factors in the chemical character of river water has been stressed. Clear Creek, which has its source in the Bighorn Mountains, flows for several miles through a region of Precambrian granites. These rocks are not


Yellowstone River
Miles City
Little Missouri River
Sheridan
Bighorn Mountains
Arvada
Buffalo
Gillette
Belle Fourche River
Midwest
Cheyenne River
Rattlesnake Range
Casper
North Platte
Lusk
10 0
50 Miles

From landforms map by Erwin Raisz, 1939

Fig. 2--Map of the land forms of the Powder River drainage basin and surrounding areas

readily disintegrated by the solvent action of water and contribute only small amounts of mineral substance to Clear Creek. Near Buffalo, Wyoming, the creek water is characterized by low concentrations of dissolved solids that may be less than 50 ppm. The Little Powder River, on the other hand, heads in upland country and drains an area that is largely underlain by Tertiary sandstones and shales. The erosive properties of these rocks are much greater. Sandstones and shales in this area are readily attacked by flowing water and yield considerable amounts of mineral solids to the Little Powder River. In the vicinity of Broadus, Montana, the concentration of dissolved solids in the river water may exceed 2000 ppm.

The chemical analyses of water samples from several sampling stations in the basin were correlated with rock formations in the vicinity. Five type waters are shown in Table 1; the type name is obtained from identification of the principal rock outcrops in the immediate area. Many of the basin waters are mixed types, and correlation of these waters is difficult. Further complications arise where return irrigation flows enter a stream and modify the chemical character of the water.

In Table 1, analysis A represents a water that has been in contact with granite rocks. As previously noted, Clear Creek is a mountain stream and drains an area of igneous and metamorphic rocks. Silica is an important constituent in the composition of the mineral substance of the

Table 1--Chemical character of type waters (Analyses in percent of anhydrous residue), September 1949

Mineral constituent	Water type Granite water A	Limestone water B	Gypsum water C	Shale water D	Mixed water E
Silica (SiO_2)	27.6	6.4	1.4	0.3	9.7
Calcium (Ca)	23.2	20.4	16.7	6.9	16.8
Magnesium (Mg)	2.2	10.8	5.5	3.8	5.7
Sodium and Potassium (Na+K)	1.2	1.2	7.6	20.3	7.7
Carbonate (CO_3)	37.0	54.6	14.0	8.1	32.9
Sulfate (SO_4)	7.4	3.6	52.8	60.0	25.8
Chloride and Nitrate ($Cl+NO_3$)	1.4	3.0	2.0	0.6	1.4
TOTAL	100.0	100.0	100.0	100.0	100.0
Dissolved solids (ppm)	43	158	727	2020	155

A--Clear Creek near Buffalo, Wyo.
B--Middle Fork Powder River near Barnum, Wyo.
C--Middle Fork Powder River above Kaycee, Wyo.
D--Little Powder River near Broadus, Mont.
E--N. Fk. Crazy Woman Creek above Billy Ck. near Buffalo, Wyo.

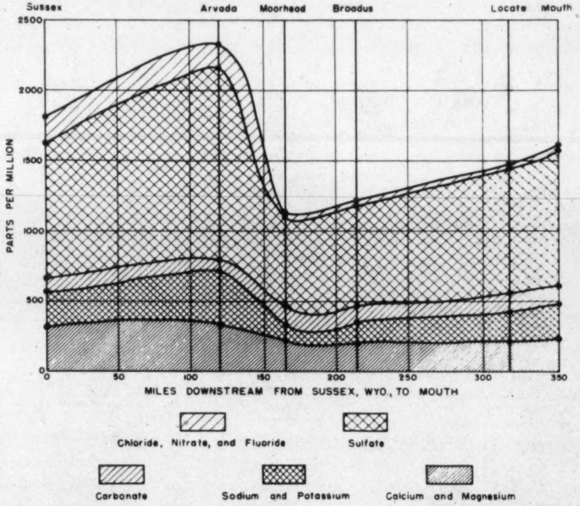


Fig. 3--Composition of the Powder River water at low stage, Sept. 11 - 14, 1949

Table 2--Percentage composition of water in the Powder River drainage basin, September 10 - 14, 1949

Station	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride and nitrate ($Cl+NO_3$)	Dissolved solids
								ppm
S. Fork Powder River near Kaycee, Wyo.	0.8	11.7	2.8	16.8	4.1	52.1	11.7	1950
Powder River at Sussex, Wyo.	0.5	12.5	4.2	14.0	5.4	52.5	10.9	1830
Powder River at Arvada, Wyo.	0.3	10.2	4.2	15.8	3.9	58.4	7.2	2330
Powder River at Moorhead, Mont.	0.5	11.2	7.4	10.2	11.6	58.1	1.0	1130
Powder River near Broadus, Mont.	0.7	10.3	6.6	12.2	10.2	58.9	1.1	1210
Powder River near Locate, Mont.	0.7	9.4	5.4	15.0	8.3	59.6	1.6	1470
Powder River at mouth near Terry, Mont.	0.6	9.6	4.4	16.1	7.5	60.0	1.8	1610
Middle Fork Powder River near Barnum, Wyo.	6.4	20.4	10.8	1.2	54.6	3.6	3.0	158
Middle Fork Powder River above Kaycee, Wyo.	1.4	16.7	5.5	7.6	14.0	52.8	2.0	727
Middle Fork Powder River at Kaycee, Wyo.	1.1	12.7	5.2	12.6	10.2	49.9	8.3	1010
Middle Fork Powder River near Kaycee, Wyo.	0.6	12.4	4.9	13.5	10.2	51.2	7.2	1090
Beaver Creek near Barnum, Wyo.	2.0	14.8	7.0	6.9	14.0	54.4	0.9	845
Red Fork near Barnum, Wyo.	2.5	15.2	7.5	9.0	29.5	29.5	6.8	387
N. Fork Powder River near Mayoworth, Wyo.	2.4	13.4	6.4	10.1	21.2	46.3	0.2	623
N. Fork Powder River near Kaycee, Wyo.	0.7	9.4	5.2	15.2	8.5	59.4	1.6	1660
Salt Creek near Sussex, Wyo.	0.2	6.9	3.0	21.1	3.9	60.8	4.1	3750
N. Fork Crazy Woman Creek above Billy Creek, near Buffalo, Wyo.	9.7	16.8	5.7	7.7	32.9	25.8	1.4	155
N. Fork Crazy Woman Creek below Middle Fork near Buffalo, Wyo.	1.7	12.6	7.4	8.9	14.7	53.8	0.9	754
Crazy Woman Creek near Buffalo, Wyo.	0.5	11.0	7.2	10.1	7.8	62.3	1.1	1380
Middle Fork Crazy Woman Creek near Greub, Wyo.	5.3	20.9	6.3	3.0	28.1	35.8	0.6	302
Poison Creek near Greub, Wyo.	0.5	14.3	4.4	10.3	3.9	65.8	0.8	3250
S. Fork Crazy Woman Creek near Greub, Wyo.	1.6	11.1	6.8	11.9	16.7	51.3	0.6	881
Clear Creek near Buffalo, Wyo.	27.6	23.2	2.2	1.2	37.0	7.4	1.4	43
Clear Creek near Arvada, Wyo.	0.5	11.3	7.6	9.6	10.0	60.1	0.9	1170
Piney Creek at Kearney, Wyo.	9.6	24.5	6.1	0.8	45.4	12.3	1.3	114
Lake De Smet, Wyo.	1.4	7.6	6.3	16.2	14.3	52.8	1.4	698
Little Powder River near Broadus, Mont.	0.3	6.9	3.8	20.3	8.1	60.0	0.6	2020

water. The low concentration of dissolved solids, 43 ppm, reflects the low solubility of rocks above Buffalo.

The limestone-type water reported in analysis B is a calcium carbonate water of moderate concentration. This water contains less silica than the granite type and magnesium is present in significant amounts. The Middle Fork Powder River near Barnum, Wyoming, drains an area that is underlain by the limestones in the Phosphoria formation and the Madison formation and by the porous Bighorn dolomite.

Downstream in the vicinity of Kaycee the water of the Middle Fork Powder River has been altered in chemical character from a limestone type to that of a gypsum type, as shown in analysis C. This change is the result of the river's crossing an area that is underlain by gypsum beds, gypsiferous shales, and siltstones.

A typical shale-type water, shown in analysis D, is illustrated by the water in the Little Powder River near Broadus, Montana. This water contains considerable sodium sulfate which has been leached from Tertiary and Cretaceous shales and sandstones above Broadus.

An example of a mixed type is the water in North Fork Crazy Woman Creek above Billy Creek, near Buffalo, Wyoming. Silica, as shown in analysis E, is intermediate between the shale and granite waters; carbonate and sulfate are present in approximately equal quantities. This stream has its headwaters in Precambrian granites and flows successively over Paleozoic limestones and dolomites and over an area that is underlain by Cretaceous shales.

Table 2 shows the percentage composition of mineral solids in water samples that were collected from 27 sampling points during the period September 10 to 14, 1949.

Main stem water from Sussex to mouth--From Sussex, Wyoming, to its confluence with the Yellowstone River near Terry, Montana, the Powder River meanders over a course of approximately 350 mi. Changes in chemical character of the river water occur largely as the result of tributary inflow and other accretions. Variation in concentration of sulfate is evident from Table 3.

Table 3 - - Concentration of sulfate in Powder River water, September, 1949

Station	Distance downstream from Sussex, Wyo.	Sulfate
	mi	tons ac ft
Sussex, Wyo.	0	1.31
Arvada, Wyo.	119	1.85
Moorhead, Mont.	165	0.89
Broadus, Mont.	212	0.97
Locate, Mont.	318	1.20
Mouth	350	1.32

In all reaches of the river the amount of sulfate in the water exceeded 50 pct of the total mineral content and ranged from 53 pct at Sussex to 60 pct at the mouth. The increase at Arvada was due partly to discharges from Crazy Woman Creek, about 12 mi upstream, and partly to accretions from other sources between Sussex and Arvada. The decrease at Moorhead is explained by the discharge of less mineralized water from the mouth of Clear Creek. At Locate the concentration of sulfate again increases, largely as the result of salt contribution from the Little Powder River. The variation in composition of the main stem water is shown graphically in Figure 3 where concentrations of the principal ions are plotted as parts per million for Sussex and stations downstream.

Summary--The variation in chemical character of water in the Powder River basin is largely the result of geological influences. Geochemical correlation of the water requires knowledge of the occurrence of the waters for which chemical analyses are available. Rock solubilities and erosive characteristics are determinative factors in studies of geochemical relationships of natural waters.

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RECENT ACTIVITY OF USU VOLCANO, JAPAN, WITH SPECIAL REFERENCE TO THE FORMATION OF SYOWA SINZAN

Kenzo Yagi

Abstract--Recent activity of Usu Volcano began on December 28, 1943 with severe earthquakes at the northern foot of the volcano, and ended in September, 1945, with the formation of Syowa Sinzan, a new parasitic volcano on the eastern foot. This activity was characterized by a series of severe earthquakes of various kinds, marked topographical deformation, paroxysmal eruption, and protrusion of a mass of juvenile magma. Syowa Sinzan is composed of a dome of new lava, protruding from circular, platform-shaped "Roof Mountain," which is an upheaved part of the ground, and consists mainly of Somma lava of Usu Volcano. The new lava is a hypersthene dacite, similar to the lavas of the other domes of Usu, and the Somma lava is an olivine-augite-hypersthene andesite, sometimes including large crystals of calcic plagioclase. The petrographic significance of the new lava and its intimate relation to the mode of activity of the volcano is discussed.

Introduction--Usu Volcano is situated on the southern flank of Toya lake, in the southwestern part of Hokkaido, Japan (see Fig. 1.) This volcano has been famous for its activity throughout historic time. After more than thirty years of dormancy beginning in 1910, a new period of activity started on December 28, 1943, and ended about September, 1945, with formation of a new parasitic volcano, Syowa Sinzan on the eastern foot of Usu. (Syowa Sinzan is also spelled Showa Shinzan. Both have the same pronunciation, meaning a new mountain of Syowa (or Showa) era.) This afforded an excellent opportunity to observe birth and development of a volcano. Therefore, the activity has been studied from various aspects, and much information has been obtained by numerous Japanese investigators. In view of the importance of the activity and the difficulty of access to many of the papers, some of these results are reviewed in the present paper. For more details, the reader is referred to the paper by MINAKAMI, ISHIKAWA and YAGI [1951], of which free use was made in this paper.

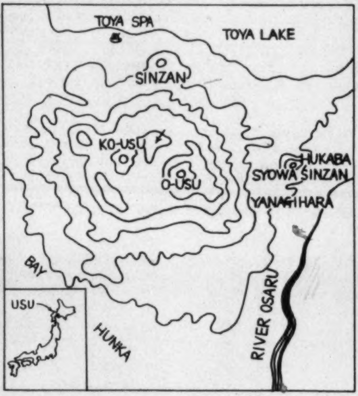


Fig. 1--Map of Usu Volcano

Previous activity of Usu Volcano--Somma of Usu was formed on the Rusutu formation composed of pyroclastic materials and diluvial sediments on the southern flank of Toya Lake, a caldera lake about ten kilometers in diameter. The Somma lavas are all two-pyroxene andesites with or without olivine. On the crater, about two kilometers in diameter, on the top of this Somma, stand two central domes, called O-usu and Ko-usu respectively. They are composed of hypersthene dacite. O-usu, the younger of the two is estimated to have been formed about 150 years ago, while the date of formation of Ko-usu is unknown, probably more than one thousand years ago, judging from the extent of erosion on the dome.

In 1822 and 1853, there was severe activity, resulting in the formation of abundant mud flows. In the activity of 1910, violent eruption on the northern foot of the volcano created 45 new explosive craterlets aligned in the east-west direction, and a new mountain called Sinzan, 211 m above sea level, was formed by an upheaval of the ground of about 150 m. Toya Hot Spring was also formed as a result of the activity. However, no juvenile lava appeared on this occasion.

Recent activity, 1943-1945--After the activity of 1910, Usu was dormant for 34 years, until December 28, 1943, when suddenly the new period of activity began with series of severe earthquakes localized at the northern foot. The activity may be conveniently divided into the following three stages [ISHIKAWA, 1950].

(1) Pre-eruption stage: December 28, 1943 - June 22, 1944.
(2) Paroxysmal eruption stage: June 22 - October 31, 1944.
(3) Dome building stage: November 1, 1944 - September, 1945.

Pre-eruption stage started with violent earthquakes, which were strongly felt by the inhabitants of Toya Hot Spring. When the earthquakes ended in February, 1944, minor earthquakes, supposedly of extremely shallow origin occurred first in the vicinity of Yanagihara, and then at Hukaba, both on the eastern foot of the volcano. Simultaneously the ground near the epicenters at Hukaba began to rise rapidly, accompanied by the formation of numerous cracks and fissures on the surface. At the end of this stage, the total upheaval of the ground amounted to about 50 m. The rate of rise was 20-150 cm per day during June.

Paroxysmal eruption stage began on the morning of June 23, six months after the beginning of the activity. The first eruption took place on the top of the uplifted area. Water vapor was the dominant material emitted, but it was accompanied by small amounts of mud and ash. This was followed by numerous small mud eruptions, which had a similarity to geyser action in that the activity was caused by the superheated underground water. On July 2, the greatest activity thus far began and a large amount of ash, estimated at about 2×10^6 tons, was ejected. This covered Sobetu village, about two kilometers northeast of Hukaba. This eruption was undoubtedly caused by vapor pressure in the juvenile magma. This was succeeded by numerous violent eruptions with the formation of seven new craters, arranged in a semi-circle on the top of the uplifted area.

The earthquakes increased in frequency, and were accompanied by the marked topographical deformation of the ground. Two kinds of earthquakes, conveniently called A- and B-types, were noted; the former occurred at depths between two and five kilometers on the southern side of the volcano, while the latter originated at extremely shallow depth at Hukaba. A-type earthquakes were similar to so-called tectonic ones, while notable characteristics of the B-type were ascribed to the extremely shallow depth of their hypocenters, and to complex structure at or near the surface [MINAKAMI, 1949]. During this stage, nues ardentes also blasted several times from the top toward the Toya lake, and though the temperature was not very high, these caused severe damage to the vegetation. By the end of October, the uplifted area, formerly about 130-160 m above sea level, was elevated to nearly 250 m above sea level, forming a platform-shaped mountain called Roof Mountain. No juvenile lava appeared at the surface, although a large amount of ash was ejected during this stage.

The dome building stage occurred after the last eruption of October 31, 1944. No notable explosive activity took place, and in the middle of November a black mass of new lava was observed to rise at the center of the area surrounded by the craters on the top of Roof Mountain. This mass continued to rise with a remarkable rapidity, at a rate of about 60 cm per day, until it formed a pyramid-shaped dome on Roof Mountain. This dome attained the maximum height in September, 1945, and then subsided only slightly in the next month. It is now 405 m above sea level, or about 150 m higher than Roof Mountain (Fig. 2 and 3).

Earthquakes that followed the growth of the dome were different from the preceding ones, and are grouped as C-type. All of them showed an astonishing similarity even in minute detail, and their hypocenters were below the dome, less than 500 m deep. M. Mimatsu, the old postmaster of Sobetu village, constructed a diagram to illustrate the growth of the dome and Roof Mountain, based on his numerous precise sketches (see Fig. 4). An inspection of the diagram shows that the rate of upheaval was not constant but varied from time to time. Since October, 1945, there has been no noticeable activity.

Morphology and geology of Syowa Sinzan--As shown in Figure 5, Syowa Sinzan is composed of Roof Mountain and the dome [OKAMOTO, 1949]. Roof Mountain is a nearly circular platform, about 800-1000 m in diameter, and is surrounded by slopes, 20-40 degrees in inclination, except on the western side. The height is about 170-200 m above the surrounding area, and the highest point is 274 m above sea level. Its top surface is undulating, showing several depressions, sometimes filled with water. These are remnants of the former craters. Roof Mountain is chiefly composed of Somma lava of the type at Usu Volcano, pumice beds, volcanic ash, and ejecta of the present activity. In some parts are exposed Rusutu formation and Takinoue liparite lava, of which the basement of Usu Volcano is composed. Usu Somma lava is broken into large blocks, one to ten meters in maximum dimension which are usually covered by pumice beds more than a meter in thickness.

Fig. 2--Syowa Sinzan seen from the north; the dome is covered with thick vapor

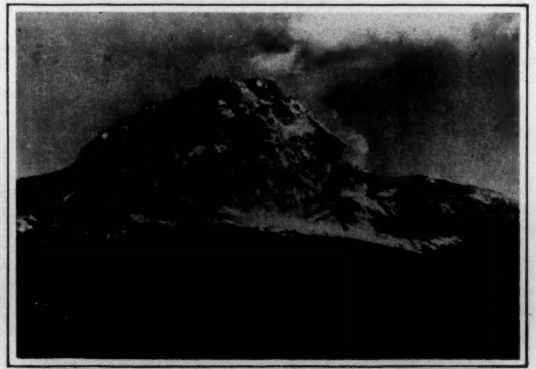


Fig. 3--Dome of Syowa Sinzan seen from the west; note fumarolic activity on the western escarpment

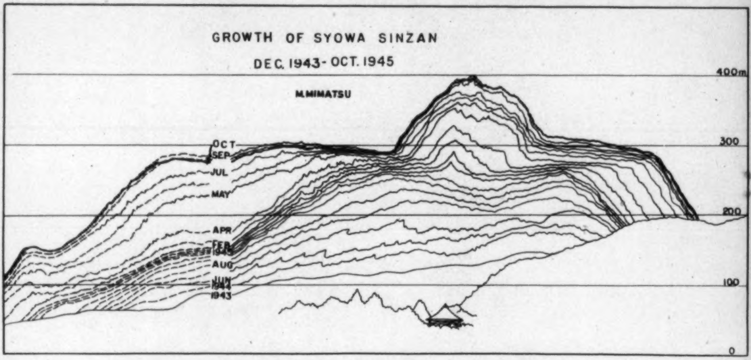
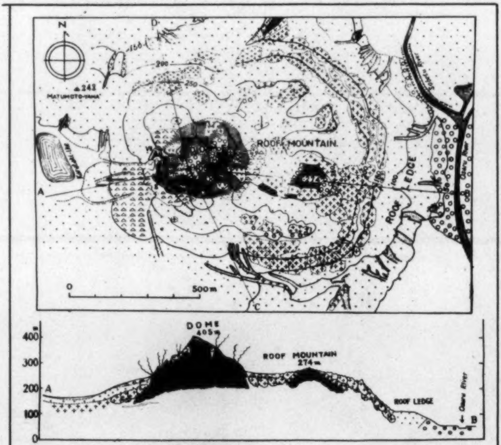


Fig. 4--Diagram illustrating the growth of Syowa Sinzan by M. Mimatsu; heavy line indicates the present outline since slight subsidence in October, 1945


N
D
150
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MATUMOTO-YAMA
ROOF MOUNTAIN
ROOF
EDGE
A
B
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Sobetsu River
Osaru River
DOME
405m
ROOF MOUNTAIN
274m
ROOF LEDGE
400
300
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D
C
1
2
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4
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Fig. 5--Geological map and profiles of Syowa Sinzan, prepared by Yagi and Okamoto in 1948; (1) new lava, (2) burnt clayey substance, (3) volcanic ejecta, (4) mud, (5) volcanic ash, (6) Somma lava of Usu, (7) clay, (8) gravel beds, (9) tuff, (10) Takinoue lava

The dome is situated a little westward from the center of Roof Mountain, and is composed chiefly of new lava, which forms several large slabs separated by intervening narrow crevices. The surface of the dome is, however, largely covered by thick layers of clayey materials, which are commonly burnt into reddish-brown brick-like substance through the heat emanating from the new lava. On the surface of the slab-like masses are many long striations arranged in parallel rows caused by intense friction during the upward movement. Blocks of Somma lava are found embedded in clayey substance. It is worth noting that gravel beds composed of pebbles of granitic, andesitic, or sedimentary rocks, and loose sand are present at many localities on the dome. The very summit is also covered by such a bed, about two meters in thickness. Sometimes tuffaceous sediments are also found covering the new lava. For these reasons, exposures of the new lava are limited to a narrow area, the best outcrop being found on the western precipice. The new lava never forms large blocks, but is always broken into irregular or wedge-shaped pieces, less than 20 cm in size. This fragmental character is probably due to the crushing effect of upward movement on the lava, which had already solidified before it reached the surface. In some crevices red-hot lava could be observed, and the temperature measured was as high as 980° C, but the usual range was 800-900° C. Gaseous emanations from the exposures consist mainly of water vapor, with hydrogen, hydrogen fluoride, hydrogen chloride, and boric acid. Sulphur, sassolite, gypsum, and alunogen are found in the incrustations around the fumaroles [TSUYA and SHIRAI, 1949].

An experimental model composed of an iron bar and sand grains, led NAKAMURA and MORI [1949] to infer that there should have been two columns of new lava; the one forming the dome, while the other pushed up Roof Mountain but remained under the surface. Such an underground column of lava is sometimes called a crypto-dome. KATO and SHOJI [1949] have concluded, however, from their seismic shots that there is no indication of the presence of a crypto-dome below the surface of Roof Mountain.

Petrological note--The new lava is a hypersthene dacite, homogeneous and pale grey or bluish grey in color. Phenocrysts of andesine and hypersthene are unevenly scattered in the fine-grained groundmass [YAGI, 1949]. Optical properties and estimated composition of constituent minerals together with a modal analysis by a Chayes point counter are given in Table 1. The mode of occurrence of quartz and cristobalite in the groundmass is worth mentioning. Phenocrystic quartz is absent, and in its stead occurs ocellar aggregates of quartz grains of random orientation, and also of granular cristobalite, which fill the interstices in the groundmass. It is interesting to understand why quartz did not crystallize out in the magma with silica content as high as the present dacite. In some glassy lava of O-usu, phenocrystic quartz and hornblende are sporadically present in a nearly glassy groundmass, although the bulk composition is similar to that of the new lava.

Table 1--Mineralogical composition of new lava of Syowa Sinzan

Mineralogical data		Mode of rock			
Phenocrysts	Groundmass	Phenocrysts		Groundmass	
Plagioclase	Plagioclase	Andesine	17.6	Andesine	40.5
$n_1 = 1.555$ An_{50}	n_1 not determined				
$n_1 = 1.547$ An_{39}	$(010) \wedge X' = 8° - 14°$	Hypersthene	1.9	Quartz	13.5
$2V(+) = 82° - 83°$	$An_{20} - 30$				
		Magnetite	0.6	Cristobalite	12.1
Hypersthene	Quartz				
$n_1 = 1.695$ on (110)	Cristobalite			Anorthoclase	1.6
$n_2 = 1.710$ on (110)	$c \wedge X = 40° - 45°$				
$2V(-) = 55° - 59°$				Hypersthene	3.1
mean 56.5°	Anorthoclase				
Pleochroism				Magnetite	2.8
X pale reddish brown	Hypersthene				
Y pale brown	Pleochroism			Apatite	0.1
Z pale green	X' pale brown				
Absorption	Z' pale green			Glass	6.2
$X > Y > Z$					
Composition	Apatite				
En_{55} Fs_{45} (wt pct)					
	Magnetite				
Magnetite					
	Glass				

Therefore, it seems to depend on the physical and chemical conditions whether quartz forms in the intratelluric stage or not. Except for this glassy variety, lavas of O-usu and Ko-usu domes closely resemble the new lava of Syowa Sinzan in both mineralogical (Table 1) and chemical composition (Table 3).

Table 2--Mineralogical composition of Usu Somma lava from Roof Mountain

Phenocrysts	Groundmass	Xenocryst
Plagioclase	Plagioclase	Plagioclase
n_1 = 1.564	n_1 not determined	n_1 = 1.575
(010) $\wedge$ X' = 35° - 40°	(010) $\wedge$ X' = 25° - 30°	
An_{68}	An_{40-50}	n_2 = 1.581
Hypersthene	Pigeonite	An_{89-90}
n_1 = 1.696 on (110)	n_1, n_2 not determined	
n_2 = 1.712 on (110)	c $\wedge$ Z = 45° - 48°	
Pleochroism		
X pale reddish brown	Magnetite	
Y pale brown		
Z pale green	Apatite	
Absorption		
$X > Y > Z$	Glass	
Composition		
En_{53} Fs_{47} (wt. pct)		
Augite		
n_1, n_2 not determined		
non-pleochroic		
Olivine		
Magnetite		

Usu Somma lava, which constitutes the greater part of Roof Mountain, is an olivine-augite-hypersthene andesite. Optical properties and estimated composition of the constituent minerals are given in Table 2. Presence of large xenolithic plagioclase crystals, sometimes as long as ten cm, deserves special mention. Homogeneous crystals of An_{89} composition are surrounded by a thin marginal zone of labradorite, An_{68}, which is similar to the phenocrystic plagioclase in the host rock. In some volcanoes of Japan, such an occurrence of calcic plagioclase (mostly anorthite) is not rare [ISHIKAWA, 1950], and always has features in common. It is inferred that such anorthite crystallized out very rapidly in parts rich in Al_2O_3 owing to contamination of the magma by country rock. After being distributed throughout the magma, these xenocrysts were coated by thin films of more sodic plagioclase, usually labradorite, in equilibrium with the surrounding magma.

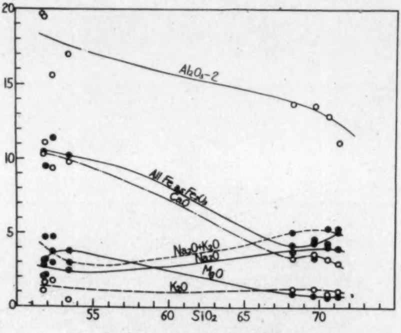

Fig. 6--Normal variation diagram of the lavas of Usu Volcano

Table 3--Chemical composition of the lavas of Usu Volcano

Constituted	A	B	C	D	E	F
SiO_2	69.74	68.26	71.25	70.60	53.46	46.04
TiO_2	0.45	0.36	0.43	0.36	1.06	0.06
Al_2O_3	15.59	15.77	13.21	15.00	18.99	34.36
Fe_2O_3	1.52	1.91	3.19	1.37	2.75	0.88
FeO	2.59	2.15	1.96	2.49	6.74	0.00
MnO	0.08	0.31	0.27	0.09	0.22	0.00
MgO	0.85	0.99	0.84	0.77	3.82	0.05
CaO	3.63	4.37	3.10	3.30	9.79	17.92
Na_2O	3.43	3.83	4.02	4.42	2.47	1.18
K_2O	1.36	1.29	1.15	0.98	0.48	0.09
H_2O+	0.67	0.51	0.50	0.69	0.33	n.d.
H_2O-	0.23	. . .	0.25	0.12	0.20	0.20
P_2O_5	0.22	0.18	0.46	0.21	0.32	n.d.
Total	100.36	99.93	100.63	100.40	100.63	100.93

A--New lava, Syowa Sinzan, analysis by Yagi.
B--O-usu dome lava, O-usu, analysis by Geological Survey of Japan.
C--Ko-usu dome lava, Ko-usu, analysis by Yagi.
D--Hornblende and quartz-bearing glassy dacite, O-usu, analysis by Yagi.
E--Usu Somma lava, Syowa Sinzan, analysis by Yagi.
F--Bytownite in the Somma lava, Syowa Sinzan, analysis by Yagi.

When all available data on the chemical composition of lavas of Usu Volcano are plotted on the usual variation diagram (see Fig. 6), it is significant that all lavas are grouped into two types: The one is basaltic andesite of Somma lava type, and the other dacite of dome lava type. Lavas of intermediate composition are completely lacking. Such abrupt changes from mafic to felsic rocks are also found in some other volcanoes of Japan. Complete absence of intermediate composition is an interesting problem, solution of which needs future study.

It was formerly suggested that the dome lava of O-usu was derived from the mafic original magma through the gravitative differentiation during the upward movement from the reservoir to the surface. It is apparent, however, that such differentiation in situ was impossible owing to the solid state or extremely high viscosity of the lava when it was extruded. Therefore, such differentiation should have occurred within the magma reservoir itself, and formed a part entirely different from the main part of the magma. It is interesting, therefore, that the dome lavas show a close similarity in their composition, in spite of long intervals between the formation of these domes, probably more than 1000 years. It is concluded that there has been no differentiation within the portion of the magma reservoir throughout this period. This is striking when compared with Parícutin volcano, lavas of which show a noticeable change in chemical and mineralogical composition within a course of only two years [WILCOX, 1951].

Mechanism of activity of Usu Volcano--The preceding description shows that the recent activity of Usu has many striking features, such as a series of severe earthquakes, marked topographical deformation, violent explosive activity, and extrusion of a solidified mass of new lava. It is interesting that such remarkable characteristics, quite unusual in many volcanoes, are very common in this volcano. As described before, the 1910 activity had also a great similarity to the recent one, except that there was no extrusion of solid lava mass in the former activity, although the

Sinzan was upheaved by a crypto-dome under the surface. O-usu and Ko-usu domes on the crater have a complete similarity to the Syowa Sinzan, not only in their morphology and structure, but in their petrographic character. Although no detailed records of their activity are left, similarity in their character makes the inference probable that the two older domes were formed by a similar mechanism as the present one.

It is well known that phenomena of volcanic activity depend on the viscosity of magmas; that is, they are of larger scale if the magmas are more viscous [MINAKAMI, 1950]. In the case of Usu Volcano the dacite magma was so extremely viscous, that it was almost solidified under the surface, and moreover, in the present case, the older domes of O-usu, Ko-usu, and Sinzan prevented the lava from extruding through the already present conduit, through which the lava could have more easily reached the surface. Enormous pressure was therefore required for the movement of such highly viscous magma, and it was responsible for all the unique characteristics of the recent activity of Usu Volcano.

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VARIATIONS IN STRONTIUM ISOTOPE ABUNDANCES IN MINERALS

PART 1: MASS SPECTROMETRIC ANALYSIS OF MINERAL SOURCES OF STRONTIUM

L. T. Aldrich, L. F. Herzog, J. B. Doak and G. L. Davis

Abstract--Procedures for the determination of the isotopic abundances of Sr in mineral sources have been perfected which enable one to analyze as little as 50μ g of Sr. Variations in the isotopic ratio Sr^{86}/Sr^{88} have been found which are outside the experimental error and, as yet, unexplained, in minerals. Differences in this ratio have been observed in the Sr from two accessory minerals in the same granitic rock.

Introduction--The isotopic analysis of Sr from mineral sources has considerable physical and geophysical significance. In the first place, no such systematic examination of Sr in natural sources has been made; second, the decay of Rb^{87} to Sr^{87} with a very long half life makes it certain that some variation in the Sr^{87} content of Sr throughout geologic time exists. This variation should yield useful information about the relative abundances and geochemical properties of Rb and Sr. Finally, a measure of the Sr^{87} content of a Rb mineral should be correlated with the age of the mineral. The last two possibilities have been discussed by WICKMAN [1948] and AHRENS [1949]. The methods of analysis, measurements obtained, and some of the geophysical and geochemical implications of the results are to be discussed in two papers. This paper will discuss the analytical procedure for determining Sr isotopic abundances and those results which have little to do with the Rb content of the mineral. The second paper [HERZOG, and Others, 1953] will be primarily concerned with the Rb^{87}/Sr^{87} decay and the applications of our measurements to geophysical and geochemical problems.

A difficulty in this research has been to find procedures by which samples of Sr of the order of 50-100 μ g may be extracted from minerals and analyzed isotopically to obtain reliable abundance ratios with a precision of the order of 0.5 pct.

Instrument--The mass spectrometer used is similar to that described by NIER [1947]. The main modification of the instrument is in the ion source, which is shown in Figure 1. No ionizing electron beam was used since hydrocarbon impurities in the region of mass 90 are numerous and difficult to remove. The shield mounting plate and the posts supporting the ribbon from which ions were evaporated were made of Ta so that simple cleaning procedures using HF and HNO_3 could be used between runs. The rest of the plates of the source were made of "Advance" metal. The exit slit of the collimating pair of slits was made 0.2 mm wide so that the double collection method described by Nier could be used in this region of higher mass.

The filament ribbon from which the ions were evaporated thermally was nickel-plated tungsten. The nickel-plating kept the sample from reacting with the tungsten and inhibited the evaporation of ions of the alkali metals normally found in tungsten. This filament was 0.001 × 0.015 × 0.5 inch and was located about 1.5 mm from the exit slit of the shield. Sr ions are evaporated from such a surface at about 1500°C [ALDRICH, 1951]. The only other ions in the Sr isotope mass region which may be so evaporated are those due to the Rb isotopes. Since the Sr^{87} isotope was of paramount interest, it was essential to eliminate Rb from the samples to be analyzed.

The ion-current collector was identical in dimensions to that described by NIER [1947]. The grid resistors of the pre-amplifiers were 10^{11} and 2×10^{10} ohms respectively, the ratio being 5.20 with a deviation of ± 0.02 as determined by ratio measurements and sweep measurements under stable operating conditions. The collector assembly differed from that of Nier only in that it was made removable from the spectrometer tube in order that the assembly geometry could be adjusted for isotope ratio measurement of different elements. Figure 2 shows sweep spectra obtained by slowly varying the magnetic field for samples of strontium from commercial $SrCO_3$ and strontium from a biotite containing 12 pct radiogenic Sr^{87}. The resolution is seen to be adequate for this mass range.

The precision measurements obtained in this work were derived from the determination of three ion-current ratios using a fraction of the output from one amplifier to balance out the output

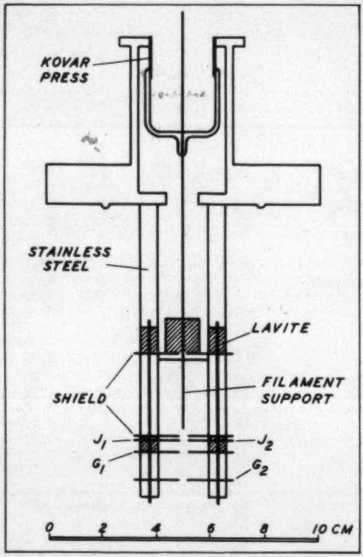

Fig. 1--Schematic drawing of ion source for analysis of Sr samples

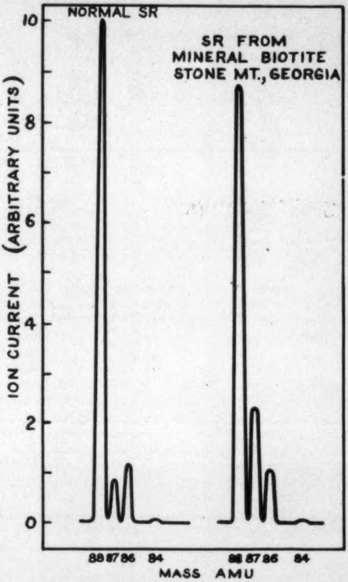

Fig. 2--Isotope distribution of strontium from "normal" and mineral sources

of the other. These ratios are given in the Appendix with the method used to calculate isotope ratios. When Rb^+ ions are present, a fourth ratio is obtained by sweeping; it is used to correct the ratio Sr^{87}/Sr^{86} for Rb present. For the measurements reported in these papers this ratio Rb^{85}/Sr^{86} was always less than 0.2. The ratio Sr^{86}/Sr^{88} is independent of the Rb content provided the Rb^+ current remains the same between the determinations of ratios A and C. The ratios Sr^{87}/Sr^{86} and Sr^{86}/Sr^{88} may be combined to give Sr^{87}/Sr^{88}. The sensitivity of this method of obtaining ratios is shown in Figure 3 where zero, balance, and off-balance conditions are shown for ratio C. It is seen that this ratio may be determined with a precision of better than 0.5 pct and we assume that other errors in the determination are random and no greater than this.

Table 1--Relative abundance of isotopes of commercial strontium

Abundance	Sr^{88}	Sr^{87}	Sr^{86}	Sr^{84}
This Work	100	8.50 ± 0.04	11.95 ± 0.03	0.67 ± 0.05
Nier	100	8.50	11.94	0.68

Analyses: Strontium reagent standard--Table 1 summarizes the measurements of the isotopic abundances of commercial Sr (Eimer and Amend $SrCO_3$) made on seven different days over a period of six months. This Sr was analyzed as chloride, carbonate, and sulfate, and all forms gave the same result. The abundances determined are compared with those of NIER [1938] who analyzed commercial Sr metal, ionizing by electron bombardment, in a 180° spectrometer. The agreement between the two sets of results seems almost fortuitous in the light of the variety of Sr isotope ratios found in this study for other samples.

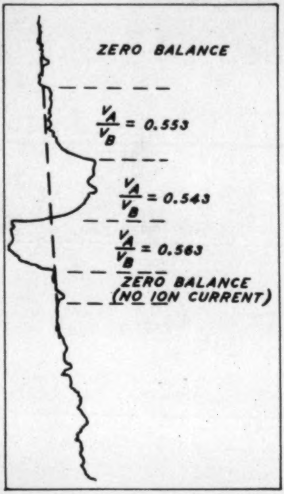

Fig. 3--Recorder trace showing balance sensitivity when measuring ion-current ratio, $Sr^{86}/(Sr^{88} + Sr^{87} + Sr^{84})$

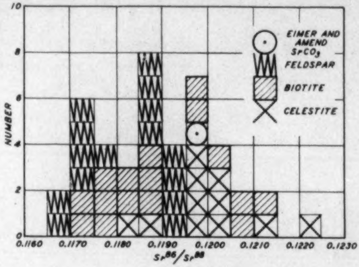

Fig. 4--Variation of ratio, Sr^{86}/Sr^{88}, in minerals

Figure 4 is a histogram showing the variation in the ratio Sr^{86}/Sr^{88} found in the minerals celestite and feldspar, and certain Rb source minerals associated with igneous rocks, for example, biotite and muscovite. A few pegmatitic and metamorphic micas are also included. It is seen that the variation in this ratio is greatest in the minerals containing the least total Sr. It has not been possible thus far to correlate this variation with inferred geologic age or any component in any of the minerals. In ten cases Sr from both feldspar and biotite from the same intrusive specimen have been measured. The Sr^{86}/Sr^{88} ratios in the two minerals agree well in only half the cases. The others vary in what seems to be a systematic fashion, but not in one which may be predicted on any known basis. Certainly further analyses are required. From the data obtained one would infer that the source of the commercial Sr was a celestite deposit.

One celestite sample showed an anomaly in this ratio which is as yet unexplained. Two parts of a hand sample were prepared in an identical manner for analysis at different times. No Rb contamination was found in either portion. Repeat analyses of one portion gave the ratio $Sr^{86}/Sr^{88} = 0.1160$; for the other, 0.1189. The ratio Sr^{87}/Sr^{88} in the two cases was 0.0839 and 0.0857. It is seen that the fraction of Sr^{88} in the Sr in the first sample is less than in the second by about two pct. This is four times the average deviation of the measurements. The geophysical process which would produce this change in such a small dimension is not known.

Conclusions--Mass spectrometric analysis of mineral sources of strontium may be made with a precision of the order of 0.5 pct when proper precautions are taken. With this tool, variations in Sr^{86}/Sr^{88} and Sr^{87}/Sr^{88} have been measured in Sr from minerals of crystalline rock and sedimentary origin. The ratio Sr^{86}/Sr^{88} has been found to vary from 0.1160 to 0.1220. The geophysical and geochemical processes by which such variations may be produced are as yet unknown. The variation in the ratio Sr^{87}/Sr^{88} is shown and discussed in a companion paper [HERZOG and Others, 1953].

The usefulness of such measurements has been shown even in a limited sampling of minerals. The results here obtained indicate that relative Sr isotopic abundance will be affected by natural variations in Sr^{86} and Sr^{88}, (and presumably the other Sr isotopes), of unknown origin as well as by the addition of Sr^{87} due to the natural radioactive decay of Rb^{87}. Care must therefore be taken to use a relative abundance criterion which is independent, as far as possible, of variations other than those due to the Rb^{87} decay, when small changes in Sr^{87} abundance are to be measured.

Acknowledgments--The mechanical skills of W. F. Steiner and B. J. Haase have been essential to the performance of the spectrometer. It is a pleasure to tell of the continued interest and support in this work of our colleague, M. A. Tuve.

APPENDIX--ISOTOPE RATIO CALCULATIONS FROM ION-CURRENT RATIO MEASUREMENTS

Four ratios are measured. If Rb is present, they are

$$\left.\begin{aligned}
A &= (Sr^{87} + Sr^{86} + Sr^{84} + Rb^{87} + Rb^{85})/Sr^{88} \\
B &= (Sr^{87} + Rb^{87})/(Sr^{88} + Sr^{86} + Sr^{84} + Rb^{85}) \\
C &= Sr^{86}/(Sr^{88} + Sr^{87} + Sr^{84} + Rb^{87} + Rb^{85}) \\
D &= Rb^{85}/Sr^{86}
\end{aligned}\right\} \ldots\ldots\ldots\ldots \quad (1)$$

For this work it is assumed that

$$Rb^{87} = 0.386\ Rb^{85} \quad \ldots\ldots\ldots\ldots \quad (2)$$

the relative abundance of these isotopes found by Nier and us. When $D \leqq 0.2$, the Sr^{87} content of the Sr is insensitive both to the assumed relative abundance of the Rb isotopes and the value of D itself.

It is seen at once that

$$\left.\begin{aligned}
Sr^{86}/Sr^{88} &= C\ (1 + A)/(1 + C) \\
(Sr^{87} + Rb^{87})/Sr^{86} &= B\ (1 + C)/C\ (1 + B) \\
(Sr^{87} + Rb^{87})/Sr^{88} &= B\ (1 + A)/(1 + B)
\end{aligned}\right\} \ldots\ldots\ldots\ldots \quad (3)$$

From (1) and (2)

$$D = Rb^{87}/0.386 \times Sr^{86} \quad \text{or} \quad Rb^{87} = D \times 0.386\ Sr^{86} \quad \ldots\ldots\ldots\ldots \quad (4)$$

and from (3) and (4)

$$Sr^{87}/Sr^{86} = [B\ (1 + C)/C\ (1 + B) - 0.386D] \quad \ldots\ldots\ldots\ldots \quad (5)$$

and

$$Sr^{87}/Sr^{88} = [B\ (1 + A)/(1 + B) - 0.386DC\ (1 + A)/(1 + C)] \quad \ldots\ldots\ldots\ldots \quad (6)$$

which with

$$Sr^{86}/Sr^{88} = C\ (1 + A)/(1 + C) \quad \ldots\ldots\ldots\ldots \quad (7)$$

gives the true isotope ratios used in this investigation. It is seen that the precision of any of the isotope ratios is limited only by the precision of the determination of A, B, and C which for the results given is 0.5 pct or less. D, as mentioned in the text, is determined by sweeping across and recording the mass 86, 85, and 84 peaks before and after the determination of the ion-current ratios.

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VARIATIONS IN STRONTIUM ISOTOPE ABUNDANCES IN MINERALS

PART 2: RADIOGENIC Sr^{87} IN BIOTITE, FELDSPAR, AND CELESTITE

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Abstract--Mass spectrometric analysis of Sr concentrates from biotites, phlogopite, muscovites, feldspars, and celestites show that variations exist in the relative abundance of Sr^{87}. Biotites contain up to 12 pct radiogenic Sr and should prove useful for geologic age determinations. Certain ancient feldspars, of age greater than 1500 million years, containing negligible amounts of Rb, yield Sr^{87}/Sr^{88} ratios less than 2.5 pct smaller than that for a geologically young strontium standard. The celestite samples analyzed show even smaller deviations from the standard Sr^{87} abundance. These analyses strongly indicate that the source material from which these crystalline rocks were derived had a Sr/Rb ratio larger by factors of five and ten, respectively, than those now accepted for average surface igneous rock or granite, but similar to those found for basalt, or chondritic material. The present limited data favor a basalt-like ratio; further work using well-dated samples is planned to narrow the permissible range of compositions and make a choice of source material possible.

Introduction

Beta activity of Rb^{87}--The beta activity of the alkali metals potassium and rubidium had been definitely established by 1906 through the observations of THOMSON [1905] and CAMPBELL and WOOD [1907 ab]. In 1937 HEMMENDINGER and SMYTHE [1937], using a high-intensity mass spectrometer, separated mass fractions from a rubidium sample and proved that the active isotope was Rb^{87}. During the same year MATTAUCH [1937] analyzed a strontium sample prepared from a Rb-rich Manitoba mica by HAHN and Others, [1937], with his double-focusing mass spectrograph and published spectra which showed that Sr^{87} was the only Sr isotope present in analyzable quantity in this mineral. This work confirmed that the rubidium decay was by beta emission, $Rb^{87} \rightarrow Sr^{87}$.

STRASSMAN and WALLING [1938] computed a half-life of 6.3×10^{10} years for the Rb decay on the basis of their work. The most recent published values are not greatly different. CURRAN and Others [1952] found 1.18×10^{-11} year^{-1} = λ, the decay constant of Rb^{87}. The half-life corresponding to this value is 5.9×10^{10} years. McGREGOR and WIEDENBECK [1952] have found $\lambda = 1.09 \times 10^{-11}$ year^{-1}. Relative geologic ages computed using any of these values will be identical, but computed absolute ages are still subject to revision as the half-life value becomes better known.

Selection of minerals--To test the potential geologic age determination method depending on the measurement of daughter Sr^{87} and parent Rb^{87} in minerals, samples in which the ratio of Sr to Rb is as low as possible are desirable. Mass spectrometric analyses have shown that in the mica, lepidolite, the strontium present may be depended on to be 90 to 100 pct radiogenic. Only a very small error will be introduced by considering it all radiogenic; hence, useful geologic age determinations can be made using lepidolite samples, by any method capable of accurately measuring the amounts of total Sr and Rb in the sample. AHRENS [1949] and his coworkers, using optical arc-spectrometry, have determined the Rb and Sr contents of a large number of lepidolites and have calculated geologic ages from these data.

Lepidolite is, however, a comparatively rare mineral, confined in occurrence almost exclusively to pegmatites. WHITING [1951] investigated a large number of minerals of more widespread occurrence by optical spectrometric techniques and found that biotite as well might be a suitable material for geologic age determination, since in the biotite samples analyzed the ratio Sr/Rb was generally below 1/10.

Whiting's work and that of HOLYK [1952] showed that some plagioclase feldspars, at the other extreme, contained only negligible amounts of rubidium, so that isotopic analysis of the small amounts of Sr present might be expected to furnish information as to the rate of change of the abundance of Sr^{87} relative to non-radiogenic strontium throughout Earth history. WICKMAN [1948] has published a similar suggestion: that Rb-free, Sr-rich material of oceanic origin might provide a means of age determination for sedimentary rocks.

In the present work, isotopic analyses of strontium samples from biotites, feldspars, and celestites have been made to investigate each of these three modes of expected Sr^{87} relative abundance variation during geologic time.

Standard isotopic abundances for Rb and Sr--If variations in relative isotopic abundances are to be investigated, it is necessary to have a standard set of abundances for each element for purposes of comparison. The isotopic composition of an element does not show local differences at a given time because of the radioactivity of one of its isotopes. It may show such differences, however, if isotope fractionation has taken place for any reason or if one or more isotopes are being added to as daughter products of any decay scheme.

The isotopic composition of rubidium was first examined by Aston in 1922. BREWER [1938], in his second analysis of Rb, obtained as abundances Rb^{85} = 72.2 pct and Rb^{87} = 27.8 pct of total Rb; no other isotopes have been discovered. NIER's [1950] work confirms Brewer's analysis. In the present work, analysis of chemically pure reagent grade RbCl yielded the value Rb^{85}/Rb^{87} = 2.591 ± 0.003, from which Rb^{85} = 0.7215 and Rb^{87} = 0.2785 of total Rb; this result is identical with that of Nier.

Strontium has been analyzed by Aston, Bluett and Sampson, Sampson and Bleakney, Nier, White and Cameron [BAINBRIDGE and NIER, 1950], and the authors. In the present work chemically pure reagent $SrCO_3$ (Eimer and Amend Batch 492327) was found to have the following composition:

$Sr^{88}/0.8252$ $Sr^{87}/0.0703$ $Sr^{86}/0.0987$ $Sr^{84}/0.0058$

The analyses from which these averages were calculated are given and compared with the earlier determinations in the companion paper to this article [ALDRICH and Others, 1953] hereafter referred to in this paper as Part 1. This investigation shows that a statement as to the source of the element analyzed should always be given with an isotopic analysis. BREWER [1938] was aware of this, for in his paper he reported that the ratio Rb^{85}/Rb^{87} varied slightly from 2.59 to 2.61 depending on what source material was used. He investigated such diverse Rb sources as lepidolites and rubber seeds. In the present work only reagent Rb was investigated. But the mineral analyses made show that variations of several per cent in the value of stable isotope ratios are indeed present in the isotopic abundances of Sr, at least, in this mass range.

Age computations--If the amount of Rb and Sr in a sample is known and the proportion of Sr which is radiogenic is known, a geologic age can be computed for the sample, using any of the half-life values given. This paper gives the results of mass spectrometric isotope analyses made at DTM (Department of Terrestrial Magnetism) of the strontium contained in 29 biotites, one phlogopite, two muscovites, and 15 feldspars for which the ratios, total Sr/total Rb, had been determined by Whiting, Holyk, and Ahrens (in preparation) at MIT (Massachusetts Institute of Technology) using optical arc spectroscopy. Eleven celestites have also been analyzed. Ages have been calculated for the mica samples using these two sets of data; these results will be discussed in a later paper.

Sample selection, mineral separation, and Sr-concentrate preparation

Sample selection--Most of the rock specimens analyzed in this research were selected by Whiting for his thesis research. Many of these were obtained from the MIT collections; others were contributed by members of the staff of the MIT Geology Department and other interested individuals. A few were added by Holyk for his thesis research. These rock samples are described and located, as completely as possible, in a paper by Whiting, Holyk, and Ahrens (in preparation) giving the results of their optical spectroscopic analyses of the mineral fractions from the samples. The celestite samples were purchased from Ward's. They are described insofar as information permits in Table 1. Since Whiting was interested primarily in determining the range of Sr/Rb ratios in various minerals, the sample suite which he selected was a nearly random one. One-third of the biotite Sr concentrates analyzed mass spectrometrically are from the Canadian shield, and most of the others are from well-scattered localities in the United States; there are a few samples from South Africa and Russian Asia.

While this suite of samples was ideal for the purpose for which Whiting collected it, as a means of testing the Sr geologic age method it suffers from the serious drawback that the rock units represented are, in most cases, not already accurately age dated by other methods; hence, one has nothing with which to compare the Sr age to evaluate the method.

Table 1--Locations and geologic ages of celestite samples

Sample	Location	Age
C-1	Modoc Township, Ontario	Presumably Precambrian (Grenville)
C-2	Travis County, Texas	....
C-3	Calabogie, Ontario	Possibly Precambrian
C-4	Penfield, New York; Lockport dolomite	Silurian
C-5	Jena, Thuringia	Permian
C-6	Lansdowne Township, Ontario	Possibly Precambrian
C-7	Girgenti, Sicily	Called upper Miocene
C-8	Chittenango Falls, New York; Rondout formation	Silurian
C-9	Clay Center, Ohio; Goleph member, Niagara group	Silurian
C-10	Fidalgo Island, Puget Sound, Washington	Possibly Triassic
C-11	Brown County, Texas	....

Physical separation of minerals--The rock samples chosen for analysis were crushed and screened and mineral fractions of biotite, phlogopite, muscovite, and plagioclase feldspar were obtained by standard methods, including high-intensity electromagnetic separation and hand removal of impurity grains under the microscope [WHITING, 1951].

Chemical processing of samples at MIT--HOLYK [1952] undertook the task of concentrating the Sr in the biotites selected by Whiting, using a method developed by AHRENS [1951] for the concentration of Li, Ca, and Sr from lepidolites. This procedure employs hydrofluoric and perchloric acids and makes use of the differences in solubility in ethanol of Rb, K, and Cs (sparingly soluble) as opposed to Ca, Sr, Na, and Li (highly soluble). The final concentrate consists mainly of the chlorides of the latter group of elements. Small but important amounts of K, Rb, Fe, Al, and the rare earths are also not removed by this processing scheme.

Sr concentration at DTM--The Sr samples sent from MIT to DTM were found to require further processing for mass spectrometric analysis. In various samples, excessive amounts of one or more of the elements Li, Na, K, Rb, Cs, Ca, Ba, Y, the rare earths, and Al, were present. Rb was especially troublesome because, when it was present, an estimated Rb^{87} correction had to be subtracted from the observed 87 peak height (87 peak = radiogenic Sr^{87} + common Sr^{87} + impurity Rb^{87}). To solve this impurity problem, ion-exchange resin column techniques were developed capable of separating alkali metal cations from the alkaline earths, and elements within each group from each other.

A shortened procedure was developed for use with the samples furnished by Holyk; in this treatment Sr was completely separated from Rb, and a concentrate could be obtained containing Sr plus as large a fraction of sample Ca as was desired for additional sample bulk [ALDRICH, HERZOG, DOAK, and DAVIS, 1953]. Figure 1 shows the separation achieved. This treatment process utilized only demineralized water and constant-boiling HCl as reagents; the behavior of the two resin columns was checked at intervals by radiotracer techniques during the processing of some 100 samples and found to be identical for both columns and unchanged during the entire series of runs.

Application of Sr concentrates to filaments--The sample prepared by ion-exchange chemistry was taken up in two drops of water and placed on the center portion of the ribbon filament with a finely-drawn capillary dropper. The celestite samples did not require any previous concentration, because of the simple composition ($SrSO_4$) of this mineral. A powder of celestite was scraped off clean mineral surfaces with a clean knife, put in suspension in water, and the colloidal-range particles taken up by dropper and applied to the filament in the same manner as the samples in solution.

Mass spectrometric analysis--The mass spectrometer design, the operating conditions, the filament used, the method of cleaning the source between analyses, and similar information concerning the mass spectrometric analysis technique used are summarized in Part 1 and given in full detail in the thesis of HERZOG [1952].

Contamination--The physical mineral separation procedures had no opportunity to introduce Sr contamination. The chemical processing at MIT presented the most important possible sources of impurity Sr. Qualitative arc spectral tests of reagents used have shown no detectable ($<10\,\mu g$)

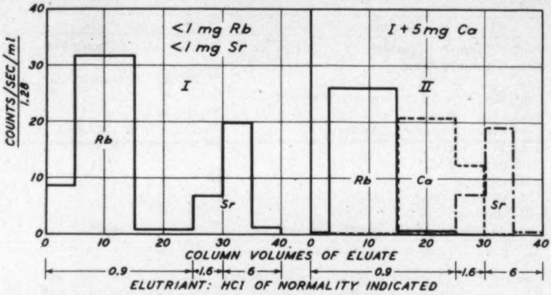

Fig. 1--Separation of Rb, Ca, and Sr, with amberlite IR 120, 50 mesh resin; column volume = 2 ml, column length = 19 CM, flow rate = 4 column volumes/hour

Sr. The reagent ethanol and tap distilled water used in these separations presented the greatest possibility of contamination. While the particular reagents used in these separations were not tested, arcings of carbon electrodes saturated with each were performed and no contamination Sr was found.

The procedures to which the samples were subjected after their arrival at DTM were subjected to rigorous contamination tests. Representative bare filaments were tested in the spectrometer. No Sr was ever seen although the omnipresent K and Na were detected in very small amounts and Rb occasionally reached the detection limit. The sample processing was checked by subjecting a 100 μg sample of a stable-iosotope Sr tracer containing 64 pct Sr^{84} (obtained from the Stable Isotopes Branch, Atomic Energy Commission) to the entire normal procedure immediately after a one-mg sample of standard Sr had been processed. In spite of the large size and vast isotopic difference of the standard Sr sample compared to the spike, no carryover contamination Sr was detected. This experiment fixed the amount of Sr that could have been introduced in DTM processing of a sample at less than 0.5 μg, the limit of detection for a 100 μg sample. There is no evidence that even this much contamination was introduced in this processing.

Results

One result of this investigation, the Sr^{86}/Sr^{88} variations, is described in Part 1. The data obtained are included in the isotope analyses given in this paper (Table 2). These variations, with a range of five per cent in the samples analyzed, make it impossible in most cases to measure amounts of radiogenic Sr by determining the value Sr^{87}/Sr^{86} alone. Hence, in the results given in this paper, radiogenic Sr is presented in terms of the ratios Sr^{87}/total Sr and Sr^{87}/Sr^{88}. Radiogenic Sr^{87} is determined by subtracting the relative Sr^{87} abundance in the Sr reagent standard (given in the introduction) from the Sr^{87} abundance determined for the sample. Since the Sr standard can at best be representative "normal" Sr for only one instant of geologic time (and probably even then only for one type of Sr deposit), a correction to the standard Sr^{87} abundance is necessary to determine the actual excess Sr that has accumulated since the mineral was formed. The size of such corrections is discussed in the section, below, on the feldspar analyses.

The analysis data presented below are discussed briefly, with reference to the possibility of a Sr age determination method, in the following discussion section.

Biotite--The mass spectrometric investigation of strontium from 29 biotites shows that this mineral contains both radiogenic Sr and "normal" Sr. Radiogenic Sr varied from zero to 12 pct of total strontium in these samples. The distribution of radiogenic Sr is shown in Figure 2 in terms of the ratio Sr^{87}/Sr^{88}. This histogram shows that there is no marked concentration of samples about any value for the samples analyzed. One or more geologic ages were inferred for each sample on the basis of previous age determinations or geologic relations. Only Tertiary samples show no measurable enrichment in strontium 87 due to the rubidium 87 decay process as

Table 2--Isotope distributions in Sr from minerals separated from granite; double collector measurements

No.	87/86		87/88		86/88		86/Sr		87/Sr		88/Sr		(87/Sr)	-0.0702
1F	. . .	0.708	. . .	0.0831	. . .	0.1174	. . .	. . .	. . .	. . .	. . .	. . .	. . .	-0.0013
5B	0.910	. . .	0.1070	. . .	0.1174	. . .	0.0953	. . .	0.0869	. . .	0.8120	. . .	0.0167	. . .
F	. . .	0.719	. . .	0.0857	. . .	0.1192	. . .	0.0984	. . .	0.0707	. . .	0.8251	. . .	+0.0005
6B	0.770	. . .	0.0909	. . .	0.1181	. . .	0.0971	. . .	0.0748	. . .	0.8223	. . .	0.0046	. . .
F	. . .	0.719	. . .	0.0850	. . .	0.1182	. . .	0.0978	. . .	0.0702	. . .	0.8263	. . .	0
7B	0.796	. . .	0.0953	. . .	0.1140	. . .	0.0937	. . .	0.0783	. . .	0.8221	. . .	0.0081	. . .
F	. . .	0.718	. . .	0.0840	. . .	0.1170	. . .	0.0969	. . .	0.0695	. . .	0.8278	. . .	-0.0007
8B	0.743	. . .	0.0878	. . .	0.1182	. . .	0.0974	. . .	0.0723	. . .	0.8244	. . .	0.0021	. . .
F	. . .	0.705	. . .	0.0838	. . .	0.1189	. . .	0.0983	. . .	0.0693	. . .	0.8267	. . .	-0.0009
9F	. . .	0.703	. . .	0.0839	. . .	0.1193	. . .	0.0986	. . .	0.0693	. . .	0.8263	. . .	-0.0009
11B	0.825	. . .	0.0996	. . .	0.1207	. . .	0.0983	. . .	0.0811	. . .	0.8148	. . .	0.0109	. . .
F	. . .	0.718	. . .	0.0845	. . .	0.1177	. . .	0.0974	. . .	0.0699	. . .	0.8270	. . .	-0.0003
12B	0.779	. . .	0.0910	. . .	0.1183	. . .	0.0973	. . .	0.0748	. . .	0.8222	. . .	0.0046	. . .
F	. . .	0.715	. . .	0.0851	. . .	0.1190	. . .	0.0983	. . .	0.0703	. . .	0.8257	. . .	+0.0001
14F	. . .	0.858	. . .	0.1005	. . .	0.1172	. . .	0.0957	. . .	0.0821	. . .	0.8165	. . .	+0.0119
15B	0.769	. . .	0.0901	. . .	0.1172	. . .	0.0965	. . .	0.0742	. . .	0.8235	. . .	0.0040	. . .
F	. . .	0.711	. . .	0.0850	. . .	0.1189	. . .	0.0982	. . .	0.0702	. . .	0.8258	. . .	0
18P	1.456	. . .	0.1714	. . .	0.1176	. . .	0.0907	. . .	0.1326	. . .	0.7716	. . .	0.0624	. . .
19F	. . .	0.725	. . .	0.0846	. . .	0.1167	. . .	0.0966	. . .	0.0700	. . .	0.8276	. . .	-0.0002
20B	0.757	. . .	0.0912	. . .	0.1205	. . .	0.0989	. . .	0.0748	. . .	0.8205	. . .	0.0046	. . .
23F	. . .	0.717	. . .	0.0850	. . .	0.1185	. . .	0.0978	. . .	0.0702	. . .	0.8261	. . .	0
26B	2.211	. . .	0.2629	. . .	0.1189	. . .	0.0856	. . .	0.1893	. . .	0.7200	. . .	0.1191	. . .
F	. . .	0.733	. . .	0.0871	. . .	0.1188	. . .	0.0978	. . .	0.0718	. . .	0.8245	. . .	+0.0016
29M	0.746	. . .	0.0889	. . .	0.1205	. . .	0.0990	. . .	0.0738	. . .	0.8214	. . .	0.0036	. . .
30B	0.801	. . .	0.0972	. . .	0.1213	. . .	0.0990	. . .	0.0793	. . .	0.8160	. . .	0.0091	. . .
51F	. . .	0.729	. . .	0.0853	. . .	0.1170	. . .	0.0968	. . .	0.0705	. . .	0.8269	. . .	+0.0003
53B	1.102	. . .	0.1320	. . .	0.1198	. . .	0.0952	. . .	0.1049	. . .	0.7944	. . .	0.0347	. . .
60B	0.800	. . .	0.0942	. . .	0.1178	. . .	0.0966	. . .	0.0773	. . .	0.8203	. . .	0.0071	. . .
62B	1.230	. . .	0.1459	. . .	0.1186	. . .	0.0933	. . .	0.1147	. . .	0.7865	. . .	0.0445	. . .
63F	. . .	0.713	. . .	0.0832	. . .	0.1167	. . .	0.0967	. . .	0.0689	. . .	0.8286	. . .	-0.0013
66M	0.740	. . .	0.0872	. . .	0.1179	. . .	0.0973	. . .	0.0719	. . .	0.8250	. . .	0.0017	. . .

compared with standard Sr. There is a tendency towards increased radiogenic content with assumed geologic age, however, with marked exceptions. The highest concentration of radiogenic Sr^{87}, 12 pct, was found in the specimen from Stone Mountain, Georgia, (Pt. 1, Fig. 2) thought to be either late Paleozoic or very late Precambrian; the age determined supported the latter interpretation. On the other hand, some samples assumed to have ages in excess of 1000 million years, and containing about the same amounts of Rb as the Stone Mountain sample, showed Sr^{87} enrichment of less than one per cent.

Biotite also showed the largest variation in the ratio Sr^{86}/Sr^{88}, as discussed in Part 1. The biotite isotopic analyses are presented in Tables 2 and 3.

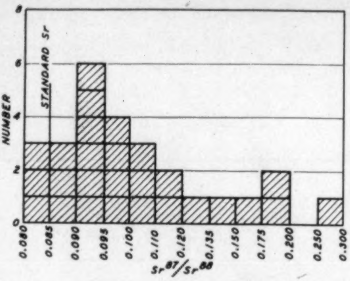

Fig. 2--Variation of Sr^{87}/Sr^{88} in biotite minerals from world-wide sources

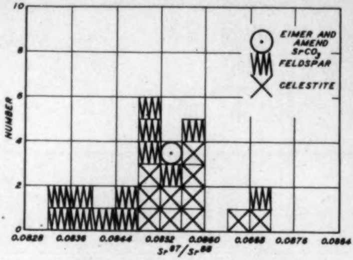

Fig. 3--Variation of ratio Sr^{87}/Sr^{88} in minerals low in Rb

Phlogopite--One phlogopite sample (18P) was analyzed using the double collector. It contained over six per cent radiogenic Sr, more than all but the very highest radiogenic-content biotites. It also had the highest Rb content reported for any sample analyzed, nearly double that of the Stone Mountain sample.

Muscovite--Two muscovites were analyzed (29M, 66M). These samples contained, respectively, 0.2 and 0.4 pct more Sr^{87} than the standard Sr. One had a Sr/Rb ratio in the low feldspar range; the other was in the biotite range. The muscovite and phlogopite data are presented with the biotite analyses.

Table 3--Magnet sweep isotope analysis for biotite

No.	87/86	86/88		87/88	86/Sr	87/Sr	(87/Sr) -0.0702	
1B	1.498	0.121	± 0.004	0.181	n	0.138	0.068	± 0.001
5B	0.910	0.1174	± 0.0005	0.1070	0.0953	0.0869	0.0167	± 0.0008
13B	0.716	n		0.0845	n	0.0699	0	± 0.001
14B	0.83	n		0.098	n	0.080	0.010	± 0.003
16B	0.800	0.119	± 0.003	0.0952	0.0976	0.0791	0.0075	± 0.001
19B	0.768	n		0.0906	n	0.0746	0.004	± 0.001
21B	0.93	n		0.110	n	0.089	0.019	± 0.004
23B	0.851	n		0.1004	n	0.0820	0.0118	± 0.0006
27B	1.58	0.119	± 0.005	0.188	0.0906	0.143	0.073	± 0.004
39B	0.78	0.118	± 0.002	0.919	0.0972	0.0757	0.0055	± 0.0005
51B	0.90	0.118	± 0.020	0.106	0.0960	0.086	0.016	± 0.004
56B	0.712	n		0.0840	n	0.0696	-.0005	± 0.0005
63B	n	n		0.12	n	0.097	0.027	± 0.020
64B	0.80	n		0.094	n	0.077	0.007	± 0.004
66B	0.915	0.119	± 0.003	0.109	0.0965	0.0883	0.0181	± 0.003

n = No analysis possible.

Error: Limits of error for 87 measurements are given in the column headed (87/Sr)-0.0702 as they most seriously influence this value. Limits of error for 86 measurements are given in 86/88 ratio, that is, in the value measured.

Feldspar--As was expected, there is considerably less spread in the feldspar Sr^{87}/Sr^{88} ratios than in those for biotite. Wherever the SrO/Rb_2O ratio obtained by Holyk is greater than ten, the 87/88 ratio is less than that for the Sr standard. However, the maximum amount the 87/88 ratio is reduced relative to standard Sr in any sample is only 2.3 pct. Where the feldspar was rich in Rb, as evidenced by SrO/Rb_2O ratio in the biotite range, there is a definite excess of Sr^{87} above that in the standard, exactly as in the case of the biotites. The other samples, with SrO/Rb_2O ratios between 0.1 and 10.0, fall in intermediate positions. There is, however, considerable overlap among groups. These findings are presented graphically in Figure 3. Fourteen feldspar concentrates were analyzed using the double collector.

The feldspar Sr isotope analyses are given in Table 2. In Table 4, the observed feldspar Sr^{87} abundances are repeated. The SrO/Rb_2O obtained by Holyk and the inferred geologic ages for each

Table 4--SrO/Rb_2O for feldspar samples with observed Sr^{87} abundances, probable ages and corrected Sr^{87} abundances

Sample	SrO/Rb_2O Holyk	Observed 87/Sr	Inferred age	Corrected Sr^{87}/Sr
			100 m.y.	
1F	>1000.	0.0689	25.	0.0689
5F	1.75	0.0707	3.0	0.0701
6F	0.645	0.0702	0.8	0.0697
7F	>1000.	0.0695	1.0	0.0695
8F	1.32	0.0693	2.6	0.0687
9F	2.2	0.0693	20.	0.0661
			12.	0.0675
11F	0.062	0.0699	3.0	0.0530
12F	2.5	0.0703	2.5	0.0699
			7.	0.0693
14F	0.90	0.0821	8.	0.0789
			20.	0.0741
15F	8.5	0.0702	2.5	0.0701
19F	0.46	0.0700	9.	0.0632
			25.	0.0380
23F	14.7	0.0702	8.5	0.0701
26F	0.27	0.0718	6.5	0.0630
			2.5	0.0688
51F	3.3	0.0705	12.	0.0697
63F	>1000.0	0.0689	10.	0.0689
			15.	0.0689
			6.	0.0689

sample are also listed in this table. From this data and the decay rate of Rb^{87}, corrections to the observed Sr^{87} abundances have been computed to take into account the amount of Sr^{87} that should have been formed in each sample on the basis of its Rb/Sr ratio and assumed age. The amount of Sr^{87} remaining after this correction is listed in the final column in Table 4. There is no apparent correlation of these amounts with assumed geologic age or any other known parameter, as the discussion section indicates.

Celestite--The Sr^{87}/Sr^{88} ratios for the celestites analyzed are quite well grouped about 0.0852, the value found for the Sr standard. This grouping may indicate that the standard strontium cannot be taken as representative of present-day oceanic Sr and that a slightly higher value must be adopted. A decision on this point awaits further information as to the geologic settings and ages of the celestite samples and in particular the strontium standard, which, from its analyses, appears to be a celestite. Figure 3 contains a histogram of the celestite Sr^{87}/Sr^{88} values, which are summarized, with the other isotope data, in Table 5.

Table 5--Celestite isotope analyses

No.	87/86	86/88	87/88	86/Sr	87/Sr	88/Sr
C-1	0.723	0.1184	0.0857	0.0978	0.0708	0.8257
2	0.706	0.1203	0.0849	0.0992	0.0700	0.8249
3	0.719	0.1179	0.0848	0.0975	0.0701	0.8267
4	0.715	0.1198	0.0856	0.0988	0.0706	0.8248
5	0.709	0.1202	0.0852	0.0991	0.0703	0.8248
6	0.716	0.1199	0.0858	0.0989	0.0708	0.8246
7	0.712	0.1205	0.0858	0.0993	0.0707	0.8242
8	0.713	0.1195	0.0853	0.0986	0.0704	0.8252
9	0.715	0.1210	0.0865	0.0996	0.0712	0.8234
10	0.710	0.1198	0.0850	0.0989	0.0701	0.8252
11	0.711	0.1221	0.0868	0.1004	0.0714	0.8224

Discussion of results

Biotite--A detailed discussion of the geologic ages computed, using the biotite-strontium analyses presented herein and the optical spectroscopic Rb and Sr analyses by Holyk, Whiting and Ahrens, will be presented in a later paper. The two sets of data, calculated age and inferred age, show a promising correlation. Twenty-one out of 32 calculated ages lie within the limits of measurement error for the ratio Sr/Rb of the inferred age. The remaining calculated ages lie outside these limits. However, in certain of these cases the inferred geologic ages chosen appear to be greatly in error. A final decision as to the limits of usefulness of the biotite-Sr method of age determination is not possible at this time.

Phlogopite--The one phlogopite sample analyzed had a very high radiogenic Sr content. The computed age for this Grenville sample agreed well with previous determinations in the same area by other methods. It appears that further investigation of phlogopite as a possible age determination material would be fruitful.

Muscovite--Muscovite also warrants further investigation on the basis of the two samples analyzed although these samples had only slight contents of radiogenic Sr. The comparison of biotite, muscovite, and/or phlogopite ages in a rock unit should provide crosschecks on the Rb-Sr method of considerable value.

Feldspar--The feldspar analyses were undertaken in the hope that variations in the isotopic composition of strontium due to the decay of Rb^{87} throughout geologic time might be systematic for igneous rocks as a whole, as would be expected if, for example, all igneous rocks separated from the same deep parent magma only a short time before solidification. The results, as is often the case, show that the actual phenomenon is not as simple as one might desire.

It was hoped that Whiting's selection procedures would yield a suite of feldspars containing only trace amounts of Rb, so that the necessity of a correction to the determined Sr^{87} abundances might be avoided. Unfortunately, only three of the 15 samples analyzed met this specification. Three others had high enough SrO/Rb_2O ratios that only very small corrections for radiogenic Sr were necessary. However, for the other samples the SrO/Rb_2O ratio extended from this high value down very far into the range of values favorable for age determination found for biotite. The corrections indicated for many of these samples are much larger than the anomaly sought.

The feldspar data of Tables 2 and 4 have been plotted against the inferred ages already discussed. This plot shows no unambiguous systematic variation of common Sr^{87}/Sr with time. However, all samples having reasonably high Sr/Rb ratios are depleted in Sr^{87} compared to biotites and the strontium standard. Two of the correction-free values, for 63F and 1F, show a depletion of only 0.0013 in Sr^{87} relative abundance (compared to the standard, 0.0702) in over 1500 million years on the basis of the inferred ages. If the simple model of igneous rock genesis just presented were valid, these values would mean that the Rb/Sr ratio for the Earth's crust determined from geochemical analyses must be quite erroneous, for it predicts that in 1500 million years an amount of Sr^{87} equal to 0.7 pct of total Sr should have been added to common strontium; this would mean, for rocks crystallized at that remote time, a Sr^{87} abundance of about 0.0630 and a correction of 0.0070 to compensate for the original assumption that the abundance had not varied from that of standard strontium in the past.

It is apparent that additional analyses must be made before the modes of variation of Sr^{87} relative abundance in surface rock can be determined. Suitable samples, in particular ancient low-Rb minerals, are at present being collected for such a study.

It appears, however, that if a systematic correction is necessary to biotite ages because the common Sr^{87} abundance (assumed constant in this work) has varied throughout geologic time, being less for common strontium trapped in any rock crystallized in the past, it will not be nearly as great as had been expected and may even be negligible for biotites where over one per cent radiogenic Sr is found; however, much larger specific corrections may be necessary because of variations that this research indicates are present in the Rb/Sr ratios in the sources of various crystalline rocks.

This evidence tends to reinforce the similar evidence of only slight variation in the relative abundance of strontium 87 throughout geologic time given by the celestite data.

Celestite--Although there can be reasonable doubt that some of the ages postulated for the celestite samples analyzed are correct, because the mode of formation of these deposits is not well understood at present, none of them showed a variation in Sr^{87}/Sr^{88} of even the order of magnitude predicted by Wickman on the basis of his geochemical Rb/Sr ratio data. It appears that the effect of the Rb decay on the isotopic composition of oceanic strontium is much smaller than expected, and may be very difficult to use as an age criterion, if indeed this effect can be distinguished from variation due to other natural processes.

The celestite data agree with and emphasize the indications of the feldspar data that presently held views as to the relative abundance and geochemical behavior of rubidium and strontium must be revised. Certainly this result should not be entirely unexpected in view of the difficulties inherent in weighing individual samples to obtain an average for a large unit such as the Earth's crust. Further, the interpretation of this average in terms of crystalline rock genesis models is of dubious value when the relative extent of such processes as granitization of sediments as opposed to intrusion of magma from depth is unknown, and other questions, such as the existence of a primitive atmosphere and ocean, and their compositions if they did exist, are still almost completely unanswered. When more information has been obtained, isotopic analysis of Sr should help to fix the relative proportions of Rb and Sr in earth units and shed much light on their respective geochemical behaviors. It appears that, in a similar manner, isotopic analysis of rock mineral samples will become a powerful tool for the investigation of abundances and geochemistry for many other pairs and groups of radioactively related elements.

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A COMPARISON OF MICROSEISMS AND OCEAN WAVES RECORDED IN SOUTHERN NEW ENGLAND

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Abstract--A comparison of ocean-wave and microseism recordings is made for two cases of very high waves off southern New England. No prominent microseism activity of the type usually associated with marine cold fronts and cyclones occurred. However, very weak fairly regular microseisms of short period, only slightly above normal background, were observed. These correlate very well with times of high wave activity rather than with that of offshore winds and are suggested as being of true surf or shallow-water wave origin. A third case is shown for control in which, following conditions similar to the above, an intense microseism storm was generated by a vigorous cold air mass moving offshore, and suggests that pressure fluctuations in this air mass are the generating mechanism.

Introduction--The effects of swell and surf on microseism generation in the western North Atlantic Ocean were considered in earlier studies by the writer [DONN, 1951, 1952a] as being negligible on the basis of what was considered strong although indirect empirical evidence. In order to investigate the effects of swell and surf more directly, several cases were studied when high waves prevailed off the rocky coast of New England and for which simultaneous wave and microseism recordings were available. A recent report [DONN, 1952b] gives the results for swell and microseisms associated with a passing hurricane. In the present study, cases were examined when very high coastal waves existed and for which there were no concurrent meteorological storms in the critical ocean area. The wave data were obtained from records made by the underwater pressure recorder of the Woods Hole Oceanographic Institution and the microseism records from Weston College Observatory, about 60 mi north. These are indicated respectively by R and W in Figures 1 and 2. The wave meter was located off the southwestern end of Cape Cod, near Cuttyhunk Island, at a depth of 78 ft.

Comparison of the data--Tables 1 and 2 show simultaneous microseism and ocean-wave height and period and offshore wind force for two cases of very high waves. In both cases the high waves were generated by a protracted flow of southerly air off eastern United States. Figures 1 and 2 show offshore pressure and wind conditions shortly before the time of maximum wave activity for both cases. The seaward passage of the air masses following the cold fronts terminated the intervals of high ocean-wave generation. There appeared to be no other areas of possible marine microseism generation at either time. Figures 3 and 4 illustrate portions of the Weston long-period, vertical-component records and of the strong local ocean wave developments respectively for the period May 11-13, 1953. Figures 5 and 6 give the same data for a portion of the period of Case 2.

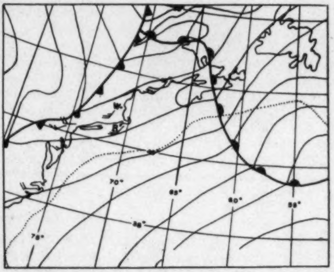

Fig. 1--Case 1, May 12, 1946, 06h 30m GMT

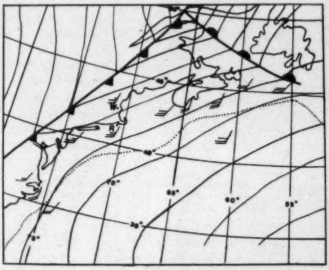

Fig. 2--Case 2, July 2, 1946, 06h 30m GMT

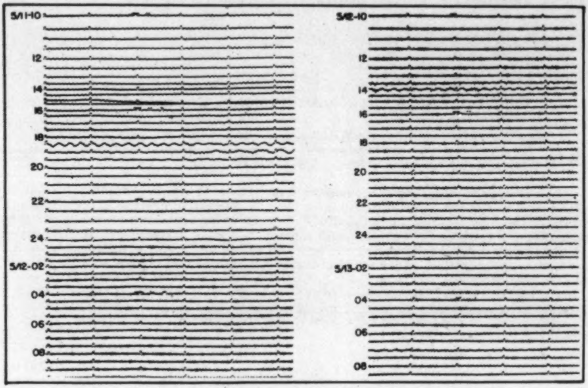

Fig. 3--Portions of the Weston long-period, vertical-component seismograms for May 11-13, 1946

Table 1--Case 1, May 11-14, 1946

Date	Time	Microseism		Wave		Wind force (Beaufort)
		Amplitude	Period	Height	Period	
1946	h m	mm	sec	ft	sec	
May 11	04 00	1.2	. . .	2.5	7.0	3
	10 00	1.1	. . .	0.9	9.0	4
	16 00	0.9	. . .	5.0	5.5	5
	22 00	1.1	2.1	13.5	6.0	5-6
May 12	04 00	1.3	2.3	10.0	7.0	5-6
	10 00	1.8	2.6	15.6	7.0	5
	16 00	1.6	2.8	7.0	8.0	5-6
	22 00	1.4	2.8	8.4	8.0	4-5
May 13	04 00	1.3	2.9	6.0	8.0	4
	10 00	1.1	3.0	. . .	. . .	4
	16 00	1.1	. . .	5.6	8.0	4-5
	22 00	1.0	. . .	7.5	7.5	3
May 14	04 00	1.0	. . .	3.9	7.5	2

It is evident that during the times of high wave activity in each case a new microseism state developed showing short-period, low-amplitude microseisms distinctly different although only slightly higher than the normal background. These are clearly different from the intense microseism storms commonly associated with strong frontal or cyclonic activity such as that illustrated in Figure 7. This shows the abrupt commencement of an intense microseism storm as recorded by the same Weston instrument. The marine weather charts in the same figure show that the time of onset of these strong microseisms correlates almost perfectly with the marine passage of a vigorous cold front and following cold air mass. Although no wave records are available, it seems definite that the southerly winds of force 6 prevailing over coastal waters prior to the frontal passage over the coast and prior to the onset of the intense microseisms must have generated waves at least as high or higher than those recorded from the conditions illustrated in Figures 1 and 2.

It has been shown [DONN, 1952a] that as cyclones, such as the above, travel seaward, the microseisms generated grade continuously into those of longer period usually associated with hurricanes or other intense atmospheric disturbances over the ocean. It is assumed that there

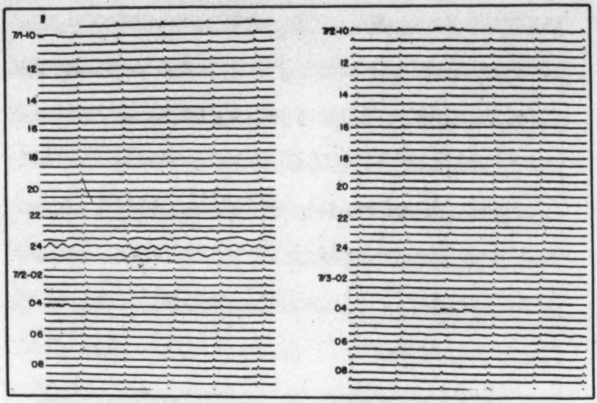

Fig. 4--Portions of the Weston long-period, vertical-component seismograms for June 30 - July 3, 1946

Table 2--Case 2, June 30 - July 4, 1946

Date	Time	Microseism		Wave		Wind force
		Amplitude	Period	Height	Period	(Beaufort)
1946	h m	mm	sec	ft	sec	
June 30	11 00	0.3	2.2	. . .	. . .	. . .
	17 00	0.4	2.0	1.0	8.0	3
	23 00	0.4	2.0	1.7	7.0	4
July 1	05 00	. . .	. . .	2.4	8.0	4
	11 00	0.6	2.0	2.2	8.0	4-5
	17 00	0.5	2.0	3.2	8.0	5
	23 00	0.7	2.1	4.8	5.5	5
July 2	05 30	0.8	2.3	7.0	6.0	5-6
	11 30	1.0	2.3	9.6	6.4	5
	17 30	1.1	2.4	11.2	7.0	5
	23 30	0.9	2.5	. . .	. . .	3
July 3	05 30	1.1	2.7	11.2	7.0	2
	11 30	0.9	2.4	8.4	7.0	4
	17 30	0.9	2.4	5.6	7.5	3
	23 30	0.7	2.5	2.7	7.8	2
July 4	05 30	0.7	2.5	5.6	7.5	2
	11 30	0.6	2.7	3.2	7.8	3
	17 30	0.5	2.8	3.2	7.0	. . .
	23 30	0.5	2.8	2.1	8.0	. . .

is no basic difference in the mechanism of origin of these relatively intense microseism storms associated with marine frontal or cyclonic activity, regardless of storm location. Several years of study have revealed that microseisms of the intense storm type have never been generated during protracted intervals of moderate to strong onshore southerly winds, but correlation with actual wave data has not usually been possible.

Discussion--According to Table 1 the growth of the system of high waves commenced between 10h 00m and 16h 00m on May 11, 1946, after moderate onshore winds had prevailed for about 18 hr. This new ocean-wave system was marked also by the abrupt appearance of a shorter and increasing

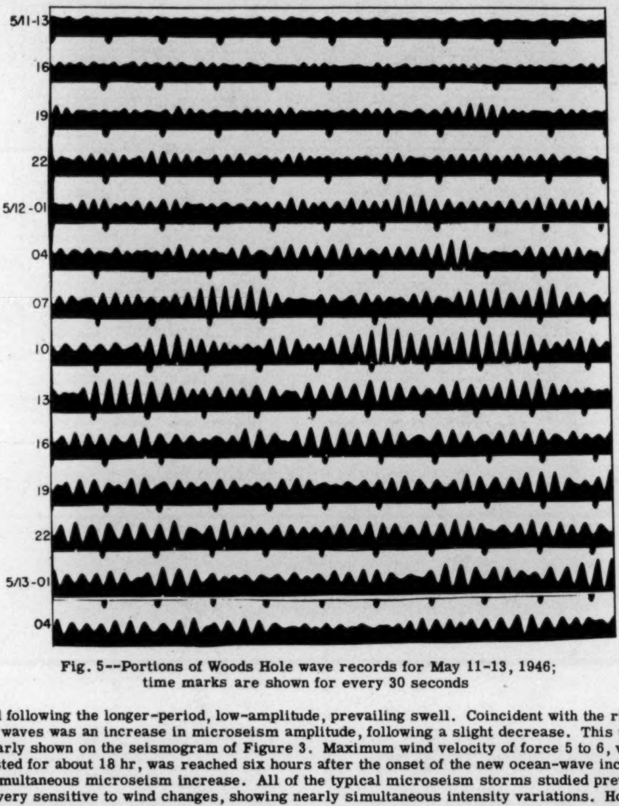

Fig. 5--Portions of Woods Hole wave records for May 11-13, 1946; time marks are shown for every 30 seconds

period following the longer-period, low-amplitude, prevailing swell. Coincident with the rising ocean waves was an increase in microseism amplitude, following a slight decrease. This trend is clearly shown on the seismogram of Figure 3. Maximum wind velocity of force 5 to 6, which persisted for about 18 hr, was reached six hours after the onset of the new ocean-wave increase and simultaneous microseism increase. All of the typical microseism storms studied previously were very sensitive to wind changes, showing nearly simultaneous intensity variations. However, these microseisms reached maximum amplitude at the time of maximum wave height, and about 18 hr after the time of maximum winds. Microseism period was relatively low, increasing slowly during the interval in which it could be measured, and showed no distinct relation to ocean-wave period, either in absolute value or relative trends. It is considered most significant that microseism amplitudes increased by only 0.7 mm to a maximum of 1.1 mm while local ocean-wave amplitudes increased by about 15 ft. It is not uncommon for Weston records to show an increase of 10 to 20 mm or more from the apparent effect of marine weather disturbances which may or may not have been attended by local high swell or surf.

The second case, Table 2, shows a new ocean-wave system to have begun by 23h 00m, July 1, 1946. This is indicated by the increase in height together with decrease in period from that of the preceding prevailing swell. An increase in microseism intensity occurred simultaneously, although the seismogram (see Fig. 4) suggests a somewhat earlier although non-measurable increase. However, there is a six-hour uncertainty in the time of beginning of wave trends. Maximum microseism activity coincides exactly with the time of maximum ocean-wave height and well

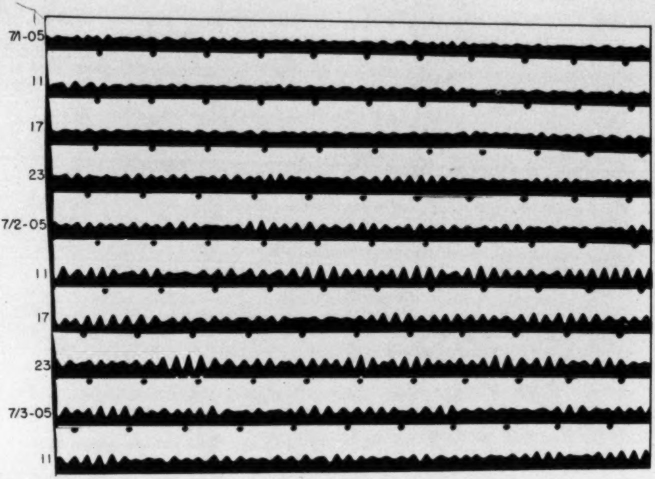

Fig. 6--Portions of Woods Hole wave records for June 30 - July 6, 1946

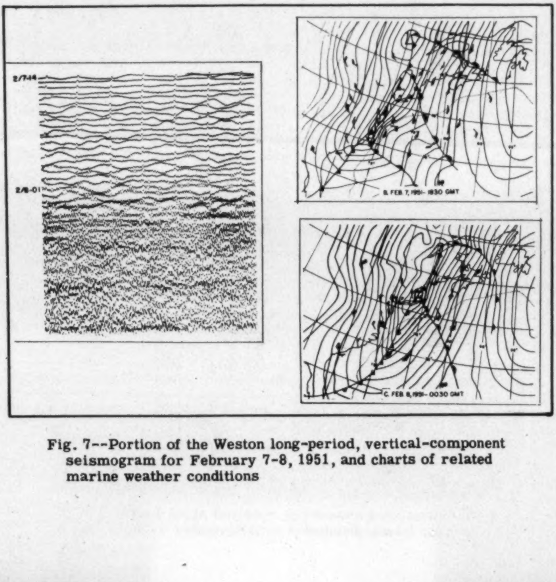
2/7-14
2/8-01
B. FEB. 7, 1951- 1830 GMT
C. FEB. 8, 1951- 0030 GMT

Fig. 7--Portion of the Weston long-period, vertical-component seismogram for February 7-8, 1951, and charts of related marine weather conditions after the time of earliest maximum wind force. During July 3, with ocean waves and microseisms still high, the wind had already fallen to the level at which no significant microseism activity occurred on June 30 and July 1. It is again significant that with a local ocean-wave height of 11 ft, microseism amplitudes were only 1.1 mm, increasing 0.8 mm above initial background. Microseism period remained low, although showing a steady slight increase with no obvious correlation to that of the ocean waves.

Conclusions--The data presented negate the importance of local high waves and surf in the generation of the microseism storms commonly associated with marine cyclonic and strong cold-frontal disturbances. This negation applies both to effects of progressive onshore waves and surf or standing waves produced through interference of incident and reflected waves. Much of the ambiguity of origin has been a consequence of the high waves, swell, and surf usually associated with severe disturbances in the atmosphere over the ocean and of the difficulty in distinguishing between their effects. Further, microseism storms with no or weak local waves or surf associated have been explained as originating in more distant surf activity. The cases given here of very high local wave activity with no resulting microseism storms and with no marine cyclonic activity seem to permit the distinction among several proposed mechanisms of origin.

The evidence tends to give further support to the recent conclusions of the writer [DONN, 1951, 1952a] and the ideas advanced earlier by GHERZI [1923, 1927] and BRADFORD [1935, 1936] that microseism storms are generated by pressure variations in the atmosphere, possibly a result of turbulence originating in winds of very high velocity or in unstable cold air masses traveling over warmer water.

The very weak microseism trends, whose amplitudes follow wave heights which in turn show considerable lag from the generating wind, are suggested as being of true shallow water or surf origin. During intervals of average surf, such microseisms are part of the background noise and become distinguishable only during times of strong local wave action. KRUG [1937] has reported similar short-period, weak microseisms from a station on Helgoland during the summer season when local surf was fairly prominent but when cyclonic activity over close ocean waters was at a minimum. It is planned to make a further study of this effect for different kinds of beach conditions.

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P AND S AT DISTANCES SMALLER THAN 25°

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Abstract--A study was made of the P- and S-phases of three European earthquakes as recorded at distances up to about 25°. One of the earthquakes occurred at a depth of about 275 km. It was well recorded at distances around 20° where the P- and S-curves were found to bend gradually and have only one branch. There is, therefore, no abrupt change of velocity at the 20° discontinuity. The second earthquake studied was shallow; the third one probably had its focus at the base of the crust. The behavior of P and S was explained on the assumption of the existence of a "soft," low-velocity layer at some depth below the Mohorovicic discontinuity.

Many observers, first Gutenberg, have noticed that P is small from distances of about five to 15°. As to S it is small or absent and sometimes more than 20 sec late. It is difficult to determine the variation of amplitude with distance because differences in instrumentation, underground conditions, the nature of the path, and possibly also variation of energy with azimuth all influence the amplitude of the wave recorded. However, observations are now so numerous and consistent that there can be no doubt about the above result.

As to S, LEE [1938] showed how scattered were the observations of S as given in the ISS for distances from about five to 15°. There was no concentration of the residuals on a mean value. JEFFREYS and BULLEN [1935] came to the same result when they undertook their revision of the time curves.

In earthquakes occurring at some depth, say 100 km or more, P and S are well recorded and their time curves are well defined. This led Jeffreys as well as Gutenberg and Richter to derive the S travel times for shallow focus shocks from those obtained for deep shocks by extrapolation. The result is of doubtful value since S as observed does not fit the time curve. It was done on the assumption that below the Mohorovicic discontinuity down to the so-called 20° discontinuity at a depth of more than 400 km the elastic constants vary continuously. The anomalous behavior of S is left unexplained.

In later years GUTENBERG [1948] has reconsidered the question and shown that small amplitudes in P and S and a certain delay could be explained on the assumption of the presence of a low velocity layer at a depth of about 80 km. This would produce a gap in the time curves such as is actually found for S. In case of P he takes this gap to be filled up by a diffracted wave.

I studied some European earthquakes well recorded at European stations up to and beyond 20° primarily in order to obtain information concerning the behavior of P and S at distances smaller than 20°. One of them was a deep shock and it was found to give additional important information concerning the nature of the 20° discontinuity. I shall give first the result of the study of this shock. It occurred off the coast of Italy on April 14, 1938. Records were collected at Strasbourg where I studied them. The epicenter, 39° 08′ N, 15° 12′ E, was also determined at Strasbourg and it differs only slightly from the one determined by GUTENBERG and RICHTER [1949]. The depth is about 275 km.

The records collected were from distances ranging from five to 23° with a few from greater distances. P and S were well recorded everywhere. Sensitive instruments recorded a small eP and two seconds later a very clear iP. Most of the ISS entries are iP up to the greatest distance 97°.9 at which P is recorded.

I am responsible for the suggestion that the strong bend in the P curve for shallow shocks around 20°, and for deep shocks at somewhat smaller distances, is not altogether continuous. In an earthquake I studied the P-phases commenced by large swings up to 19°, but from there onward there was a small swing followed by a larger one at intervals increasing with distance. This was taken to indicate that a wave refracted at a discontinuity overtook the direct wave. The time curve seemingly divided into two branches as at small distances where Pn and Pg occur [LEHMANN, 1934]. No sure confirmation of this result has been obtained, but JEFFREYS and BULLEN [1935] found that the assumption of the existence of a sharp discontinuity was consistent with the travel times as observed and constructed their time curves accordingly.

In an earthquake 270 km deep the P-curve should divide into two branches at a distance close to 16°. There are several observations of the 1938 shock at about this distance, but no small wave except the one mentioned above appears in front of the large one at distances greater than 16°. It must be concluded that the bend in the time curve is continuous, corresponding to a strong, but gradual, increase of velocity at a depth well below the depth of the earthquake. The travel times fit the Jeffreys-Bullen (JB) 1940 time curve quite well but the slope begins to change markedly at a distance slightly smaller than 16°.

S is well defined at all distances up to about 65°; most of the ISS entries are iS. The travel times are in agreement with the JB tables. There is no indication of a division of the S-phase and the bend of the time curve therefore should be gradual. Whether the 20° discontinuity is nowhere a sharp discontinuity cannot be said. There can be no doubt about the result for this earthquake. The observations that led to the assumption of a sharp discontinuity seemed convincing, but it may have been "accidental," possibly due to local structure, that the character of the first P-wave changed at a distance of 19°.

The second European earthquake studied occurred off the coast of Greece on September 26, 1932, and the third took place in the Dodecanese on April 23, 1933. The first of these was shallow; the second one seemed to have its focus at the base of the crust. Both earthquakes were recorded by many European stations, and it was hoped that a comparison of their records would show how P and S developed with distance.

It is, as already said, not easy to separate the effect of distance from that of other causes. The greatest difficulties seem to me to arise from underground structure. An illustration of this is obtained when the Göttingen and Hamburg records of the 1932 shock are compared (Figs. 1 and 2). They are from epicentral distances of about 15° and 16°. The Göttingen record may be said to be a "pure" earthquake record in which the phases are very clear. The same phases are present at Hamburg but they are severely masked by a continued, strong oscillatory motion, probably due to a kind of "sway" of the subsoil. There are other peculiarities that seemingly are characteristic of individual stations and not of epicentral distance, since they are repeated in the records of different shocks.

The 1932 earthquake was a complex one. In the records of sensitive instruments the first P wave is quite small and followed by a larger one that has a clear onset. The P travel times of most stations are found to be consistent when it is assumed that the first small wave was lost at all distances by instruments that are not very sensitive and generally at greater distances. Increase of the P group takes place after the first clear swing, but it was not found possible to correlate later onsets at all distances.

I cannot here give the details of the investigation, but shall summarize the more important results. For distances smaller than five degrees only one set of records was available, that of Sofia at Δ = 2°.3. There are some very large swings and then the records break off. Between eight and ten degrees epicentral distance there are some short-period Crimean records with quite small P's and, with one exception, badly defined S's.

As to the records of long-period instruments I should say that at a distance of about 13° their general character changes. At distances smaller than 13° P is small. It is followed by oscillations of long period with short-period motion superposed, often increasing in amplitude and continuing until S appears. On this background S, which is small, is not easily distinguished. It also happens that S is obscured by long-period waves, probably Love waves, arriving at about the same time. For these reasons the readings of S often have great uncertainty, and even when the travel time as determined from observation fits the tables, it does not always seem certain that the phase read is S. The Helwan S recorded at a distance of 12° is different from S at the European observatories; it is large and sharp. Most of the phases taken to be S are late as compared with the tables.

The long-period waves that follow the P phase were studied by SOMVILLE [1930, 1931] who took the PL phase, as he termed it, to begin some time after P, whereas others, and as I believe correctly, take it to begin at the same time or immediately after P. At Scoresby Sund in Greenland the phase is often particularly clear; the long-period waves that follow P are large and with very little short-period movement superposed on them [LEHMANN, 1950, p. 201]. The PL is a phenomenon which is confined to a certain range of distance. In the records of an earthquake obtained at Scoresby Sund at an epicentral distance of, say, five degrees there may be large PL waves,

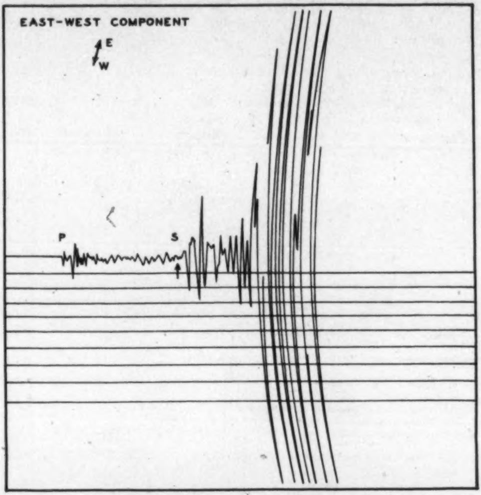

Fig. 1--Tracing of seismogram at Göttingen, Wiechert E, September 26, 1932

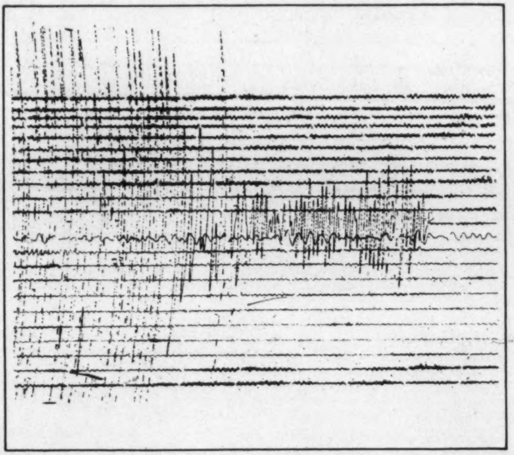

Fig. 2--Seismogram at Hamburg, Wiechert E, September 26, 1932 while they are completely absent in the Copenhagen records of the same earthquake at a distance of about 20°. As far as I know, not much attention has been paid to this phase when the structure below the Mohorovicic discontinuity has been considered. It may in some way be indicative of the layering to be spoken of later.

From an epicentral distance of about 13° the records of the 1932 shock assume what may be said to be "normal" appearance. P and S are each marked by a group of oscillations and there is much smaller motion in between. The amplitudes of P increase with distance up to about 20°; those of S up to the greatest distance for which records are available, 23°. The P travel times fit the Jeffreys-Bullen tables. S has often a small and somewhat indefinite beginning the time of which fits the tables approximately, but the onset of the large S-phase is late. The delay decreases with increasing distance until at about 20° it is small. At greater distances it increases again, but the first S onset is better defined than at smaller distances and it fits the tables approximately. The later S is exceedingly large at distances greater than 20°, as for example, in the Edinburgh record from a distance of 23°.3 (Fig. 3).

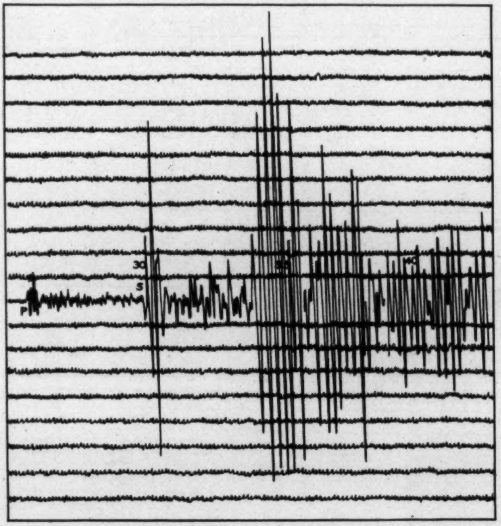

Fig. 3--Tracing of seismogram at Edinburgh, Milne-Shaw E, September 26, 1932

When the travel times of S were plotted against epicentral distance it was found that a straight line could be drawn through the points of the later, well-defined S-phases. The line as drawn had the equation $t = 8^m\ 26^s + (\Delta - 20°) \times 20.8$ sec/degree. It was not very well defined, the points having considerable spreading, but it was quite clearly indicated. The spreading of the points is probably largely due to the fact that the earthquake is of a complex nature and the phases not very clear.

The earthquake of April 23, 1933 is believed to have had its focus close to the base of the crust because the surface waves are not large, but there are no means of determining the depth accurately. The epicenter cannot be determined very accurately either. This is partly due to the fact that the stations are not well distributed in azimuth and partly to the large P wave being preceded by a smaller one that may not have been recorded everywhere.

P and S are marked by much less complex groups of oscillations than in the 1932 shock. The amplitudes vary in a similar way, but they are still small at an epicentral distance of 14°, at which distance Wien records long-period waves at the time when S should appear, and it is uncertain whether they are due to S or to L. Helwan at an epicentral distance of 7°.6 again forms an exception, having a large and clear S that fits the tables.

Up to a distance of 20° all other S readings are late as compared with the JB tables for h = 0.00. From here onwards there are several first S-onsets the times of which fit the tables, but the onsets of the large S waves are late.

The S-readings have been plotted in Figure 4. Small and indefinite onsets are marked by open circles, the earliest well-defined onsets by crosses and later onsets by dots. The curve plotted is the JB S-curve for h = 0.00. The well-defined S-onsets are seen to have their points close to the straight line drawn above the S-curve. The slope of this line is 19.6 sec/degree.

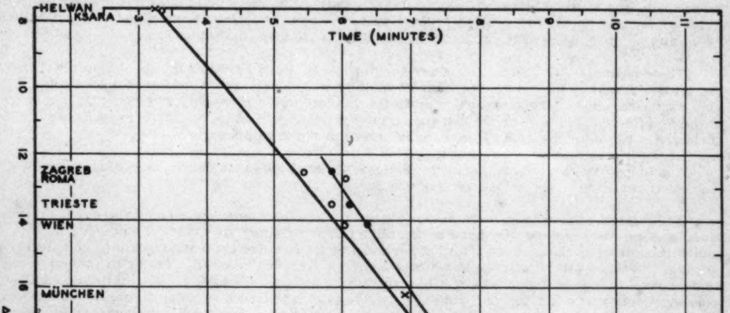

Fig. 4--Travel times of S waves, April 23, 1933

It is interesting to note that similar lines were found in two earlier studies, those of the Iceland earthquake of July 23, 1929, and of the Azores one of May 20, 1931 [LEHMANN, 1934, Fig. 3 and 4]. In the latter the line was particularly clearly indicated, because there were very few S-points below it. Its slope was 20.9 sec/degree; that of the Azores line, 21.0 sec/degree. It is hardly accidental that the travel times of the large S-phases of all four earthquakes studied fit similar lines, and an attempt will be made to interpret these lines. It should perhaps be remarked that although the lines as determined are straight lines, they are not believed to be so in a mathematical sense. They are probably representative of lines of small curvature.

On the evidence of the observations of the two shocks here studied and also of the two studied previously there can hardly be a doubt that the behavior of P and S differs. P is small in a certain range of distance, but it is nowhere absent or late as is S at the same distances. There is no P-line corresponding to the late S-line.

Gutenberg also takes P and S to behave differently and in his attempt to determine the variation of velocity with depth makes separate trial solutions for P and for S. He considers it possible, however, that there is a gap also in the P travel-time curve, that is, that there is a range of distance in which no direct P-wave arrives. The first P-wave then is taken to be a diffracted wave. The observations here considered do not confirm this hypothesis though it may not be possible to say that they disprove it. P, though small, is usually clearly marked and does not have so indefinite an onset as to necessitate the assumption of its being diffracted.

The smallness of P and the smallness or absence of S in a certain range of distance will be due to a decrease in the rate of increase of velocity with depth. For S, and probably also for P, this decrease will be strong enough to make the velocity itself decrease. The fact that S is more strongly affected than is P shows that the rigidity decreases, that is, the layer responsible for the anomaly in S and for the small P is a "soft" layer in which μ is small.

Assuming that there is no gap in the P curve we must take μ to decrease gradually, causing a gradual decrease in the velocities of P and S.

With a gradual decrease in the velocity v the rays will have downward curvature, but provided $d \log v/d \log r < 1$ (r being the distance from the Earth's center) all rays will have a deepest point and will come up to the surface again. There will be no range of epicentral distance completely in shadow, but there will be a range in which the energy received is small. Taking the velocity of P to decrease slightly with decreasing r in a certain layer, we shall have small amplitudes of P in a corresponding range of distance. Taking the velocity of S to decrease more strongly in the same layer we shall have small or negligible amplitudes of S or, possibly, no S-rays reaching the surface.

The time curve of P straightens in the range of distance where the amplitudes are small, that is, from about five to 13°, and at greater distance where the amplitudes increase owing to an increase of wave velocity with depth it again curves more strongly.

The S-curve is different. With the S-velocity, β decreasing more strongly than the P-velocity α, the rays having their deepest points in the layer of decreasing velocity will be much more widely spread, that is, the rays having the same angles of incidence as those of P will emerge at much greater distance. The corresponding part of the time curve will be practically a straight line continuing to great epicentral distances (or infinitely if $d \log \beta/d \log r \geq 1$). With β again increasing the rays will emerge at smaller epicentral distances and the time curve will run backwards until at a certain distance it turns and runs forward again. It is suggested that the S-line I have determined is the progressive branch of the time curve. The line continues beyond 20° and is associated with very large amplitudes there. This seems to indicate that with the strong increase of velocity at the 20° discontinuity a second loop in the S curve is formed.

The soft layer is at some depth below the Mohorovicic discontinuity, but it is not possible to determine this depth with any accuracy. The variation of P and S velocities with depth can be calculated when the travel-time curves are known, but the result is extremely sensitive to variations of the slope of the time curves. Present time curves are smoothed curves adapted to a steady increase of velocity with depth. They have to be altered so as to conform to observed variations of amplitude with distance. It is uncertain how this should be done for P and still more for S. Consequently solutions for the thickness of the soft layer and for the velocity variation in it and just below will have great uncertainty.

The presence of the soft layer will mainly affect rays that have their deepest points in it. For earthquakes having their foci above the layer there will, as we have seen, be great spreading of the rays that enter it at small angles with the interface, but for foci below there will be no particular spreading and no shadow. P and S amplitudes will vary with distance in a "normal" way as they are actually found to do. For a focus in the layer there will be a corresponding spreading of the rays that leave it nearly horizontally and a shadow zone for S. It seems possible that careful studies of collections of records of earthquakes having their foci at different depths may provide useful information concerning the depth and thickness of the soft layer.

A study I have undertaken lately of some North American earthquakes has shown that in eastern North America there is no such deep shadow for S as there is in Europe. S amplitudes vary in very much the same way as do those of P, and the S time curve has no loop. JEFFREYS and BULLEN [1935, p. 40] in revising the time curve also found that there was no anomaly in the North American S. This seems to mean that corresponding to the soft European layer there is in eastern North America a layer in which the velocity also decreases slightly, but in which the rigidity is greater. It should be remarked that the change needed to make the time curves differ is very slight.

The short-period surface wave Lg found in North American records by PRESS and EWING [1952] was believed to be guided by a layer underlain by a liquid layer, and it was considered possible that it would be the layer that was also responsible for the anomaly in S. However, since in eastern North America S is not detained by this layer it is not liquid. It is somewhat embarrassing that in Europe where the layer could possibly be taken to be liquid, Lg seems to be less well recorded. Evidently further investigations are needed.

Acknowledgment--The greater part of the investigation here presented was carried out in Copenhagen, but I wrote the paper during a stay at the Lamont Geological Observatory, Palisades, and I wish to express my thanks to Maurice Ewing for giving me the opportunity to do so.

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REPORT OF RESEARCH COMMITTEE ON CHEMISTRY OF NATURAL WATERS, 1951 - 1952

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The Committee has no research accomplishments to present at this time though a special report probably will be completed later. Because many members of the American Geophysical Union do not have a complete idea of the breadth of the work programs of the Geological Survey throughout the United States, it is felt that a brief report describing the activities of the U. S. Geological Survey as related to the chemistry of natural waters would be of interest. The Geological Survey is one of the principal Federal organizations that make systematic surveys to furnish basic data on the chemical characteristics of natural waters and of public water supplies with reference to their suitability for industrial, municipal and agricultural uses.

Whereas the first work on quality of water by the Geological Survey began in 1901, it was not until the last decade that these investigations became nearly Nation-wide in scope. Early investigations of the utility of surface- and ground-water supplies pointed to the need for intensive studies of chemical quality as a basis for the selection and development of industrial, municipal, and agricultural water supplies. With the realization that a water supply may be adequate in quantity but unsuitable from the standpoint of mineral content, the water resources investigations of the Survey have been broadened in many parts of the Nation to include the study of the chemical characteristics of ground and surface waters. In basic planning for the development and conservation of water supplies and evaluating their limitations for potential use, ever-increasing attention is being given by State cooperating and other Federal agencies to the influence of dissolved minerals.

A brief description of the investigational programs of the Geological Survey will be of interest to those concerned with the use of chemical quality data in specific research projects or in determining the suitability of a particular supply. The work may be divided into two principal phases; (1) study of the chemical characteristics of surface waters and (2) the chemical quality of the underground water supplies. The growing number of chemical analyses made of the Nation's water resources provides a storehouse of factual information. During the past year chemical analyses of more than 50,000 ground- and surface-water samples were made in 13 laboratories located in Washington, D. C., and throughout the country. These offices provide information, service, and data for consultation by the general public and by the Federal and local agencies.

In collaboration with studies of stream discharge, the suitability of surface-water supplies for municipal, industrial, or agricultural uses is determined by a systematic stream-sampling program at 450 points in major drainage basins throughout the United States. Studies of chemical characteristics of surface-water supplies have been under way for several years in the States of Arkansas, California, Kentucky, New Mexico, North Carolina, Ohio, Oklahoma, Pennsylvania, South Carolina, Texas, and Virginia, in cooperation with various State agencies. For more than 20 years the chemical composition of surface waters has been studied in the Colorado River Basin, encompassing Arizona and Utah and portions of Colorado, New Mexico, and Wyoming. In connection with the coordinated projects of the Bureau of Reclamation and the Corps of Engineers for the development of the Missouri River Basin, studies of the chemical quality of surface water throughout the basin have been under way since 1945. During 1951 an observation network on western streams, consisting of 33 sampling sites, was established to determine changes in quality due to return or waste flow from irrigation projects. The stations were in addition to those being operated by the Geological Survey and other Federal agencies. These stations were established to show trends in water quality for the stream quality may deteriorate progressively as agricultural development is intensified year after year. A general reconnaissance survey of the chemical characteristics of stream waters in the Columbia River Basin was begun in 1951 to provide information as to the range in mineral content of the stream waters in this region. Samples were collected on a periodic basis at several hundred stream-sampling sites in the areas specifically mentioned above and in many other parts of the country.

Studies of the chemical composition of ground waters are currently under way by the Geological Survey in practically every State. In the investigations of ground-water conditions, knowledge of the chemical composition of the waters is determined primarily for planning their use, but such knowledge is often helpful also in tracing the sources of underground waters, including both desirable and undesirable sources. For example, by determining changes in chemical composition during pumping tests on wells, the movement of saline water into fresh water sands through faulty casing has been evaluated. The chemical composition of brines is being studied in Kentucky and Michigan to determine the potentialities for development as a mineral resource. More than 5000 analyses of samples collected from ground-water sources were made during the past year throughout the United States.

An example of an intensive geochemical study would be the investigations of ground-water conditions in the central west part of the San Joaquin Valley in California, where the Geological Survey is working in cooperation with the California Division of Water Resources. The program is of interest as an example of the intensive sampling coverage necessary to appraise geochemical conditions in an area where the wells are of gravel-pack construction and commonly tap two water-bearing zones containing waters under different heads and having diverse chemical characteristics.

About a million acre feet of ground water are being pumped for irrigation from this area of 1300 sq mi, chiefly from the lower water-bearing zone of the area, and pressure levels in that zone are being drawn down at accelerated rates of 20 to 30 feet a year. In connection with proposed importation of surface water to replace the mined ground water, and possible artificial recharge of the ground-water reservoir, the poor quality of the ground waters in the upper zone presents a problem. In order better to evaluate the vertical and horizontal extent of waters of poor quality, samples of water were collected in August and September 1951 from all actively pumped irrigation wells, 803 in number. The principal cations, anions, and boron were determined. In dissolved solids the waters range from 500 to 5000 ppm and in types they range from concentrated sulfate-bicarbonate to chloride-bicarbonate waters. A progress report will be issued soon which will contain representative geochemical profiles across this complex area and will discuss briefly the areal distribution of water types.

The Geological Survey is currently undertaking a study of the industrial utility of the larger public water supplies in the United States. The latest report giving information on the chemical characteristics of the public water supplies was published in 1932. The forthcoming report, which will include a brief description of each supply as well as a complete mineral analysis, will cover about 1200 of the larger public water supplies throughout the United States.

In addition to the investigational programs directed largely toward collection of basic quality-of-water data as summarized above, the Survey also undertakes research and other special studies which are of considerable scientific interest to those working in the field of water chemistry.

The geochemistry of ground water is one element of this program. Studies of the occurrence of fluoride in ground waters are in progress in coastal areas, notably in Alabama and Virginia, as related to the geology, occurrence, and source of fluoride in ground waters. The source of nitrate and its correlation with ground water in different aquifers is being studied in Alabama and Texas. The natural softening of ground water by glauconitic sands in the Coastal Plain is being studied in Alabama, Texas, and several other areas.

Investigations of salt-water intrusion have been undertaken by the Geological Survey in many coastal areas to determine the source and extent of contamination of fresh ground- and surface-water supplies. Such studies have been undertaken in California, Connecticut, Florida, Georgia, Louisiana, Maryland, New Jersey, New York, Texas, and several other coastal states. The relation of fresh water to salt water is being intensively studied in a number of coastal areas and on a number of the Pacific islands to determine the way in which the Ghyben-Herzberg lens functions under different conditions of geology, climate, tidal range, and artificial disturbances of the aquifer and its water body. Such investigations are designed to study the mechanics of salt water intrusion, the shape of the contact between fresh and salt water in the aquifer, the changes in shape with changes in head of fresh water, and related matters.

The Geological Survey is also undertaking a study of the natural or background radioactivity of waters in order to evaluate the conditions under which and the extent to which radioactive substances may be carried in solution or suspension by surface and underground waters. Involved in such studies is the development of tracer equipment and methods for ground-water studies involving measurements in closely spaced wells to determine the velocity and direction of flow.

The Geological Survey for the past several years has undertaken a review of analytical procedures applied to the analysis of water. The fourth annual review appeared in Analytical Chemistry in February 1952. The first review, which was published in Analytical Chemistry in February 1949, covered a five-year period ended in the fall of 1948 and serves to bring together the most pertinent papers relating to the instrumental and analytical techniques involved in the demination of water quality.

Basic data on chemical quality in streams are published in an annual series of reports under the general title Quality of the surface waters of the United States. In addition, special reports are prepared dealing with the chemical quality problems in specific river basins or areas. Data on the quality of ground waters are usually incorporated in reports dealing with the availability and occurrence of the ground-water resources in an area. These project reports outline the critical aspects of problems involving the chemical characteristics of natural waters and furnish useful information needed by public and private agencies in the solution of water resources problems.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

GEIGER, RUDOLF, The Climate near the Ground, Harvard University Press, 482 pp., 1950, $5.00.

The first edition of this book was published in Germany in 1927. It represented an attempt at the first survey of microclimatological problems. Previous to that time, nearly everything written under the subject of microclimatology was to be found scattered through the literature of meteorological periodicals and papers. As Geiger points out, at the time he set to work on the 1927 edition the problem of application of the results of climatological research was indeed not new and several valuable contributions had already been made. A systematical study was needed, however, to bring together the literature and make it more conveniently available to the practitioner who "has neither time nor opportunity to look for the respective papers in the vast meteorological literature." The present American edition is the virtual equivalent of the vastly expanded and practically rewritten German third edition which came out after World War II. It serves admirably the above-stated purpose of the first edition and contains in its 41 chapters a wealth of material and results concerning a wide range of microclimatological studies carried out mostly in European countries.

Problems of microclimatic research occur not infrequently in a great many sciences whose main concern is not meteorological: biology, zoology, agriculture, medicine, and even in architecture and traffic planning, to name only a few. Indeed, it is in many of these allied sciences that some of the most outstanding progress has been made in microclimatic research methods. This book, therefore, will be of interest not only to persons professionally engaged in meteorology and climatology but also to many people associated with other scientific fields and dealing with operational planning and research. During the past decade, applications of microclimatology have experienced an expansion and development that is remarkable, and the importance of these applications is coming to be ever increasingly recognized. The book, not specifically directed to climatologists and meteorologists, will be readable to persons of moderate or general academic training in the sciences as well as to those of more advanced or specialized scientific training. The style of the American translation is smooth and conducive to easy reading. The type in which the book is set appears to be without flaw. No misprints were noticed by this reviewer.

For the benefit of those persons not having immediate access to this book, a general idea of its contents may be had from a listing, given below, of the chapter and section headings. The book is divided into two parts: Part 1 deals with the microclimate existing near the ground by virtue of its proximity to the ground surface; Part 2 deals with microclimate in its relation to topography, to plants, and to animals and man.

After an introductory chapter in which the history and definition of microclimatology are briefly recounted, the first section begins with a discussion of heat exchange near the ground. This covers five chapters: the midday heat exchange at the ground surface (the incoming radiational type); nocturnal heat exchange near the ground surface (the outgoing radiational type); true heat conduction, the normal course of ground temperature; eddy diffusion and its significance; and long-wave radiation. Section 2 concerns temperature relationships near the ground and covers four chapters: the warming process; the cooling process; the diurnal and annual course of temperature near the ground; and the temperature gradient near the ground. Section 3, made up of three chapters, deals with meteorological elements other than temperature near the ground: humidity relationships; wind relationships; and optical and acoustical phenomena, content of dust, carbon dioxide, and radium emanation. Section 4 concludes the first part of the book, taking up the influence of the ground itself on the climate near it: temperature of the ground surface, methods of measuring this temperature, the influence of the color of the surface, and the freezing of the soil; the influence of the type and condition of the soil; the air layer over water; the air layer over snow; and, finally, a supplement on the quantitative determination of the heat economy of the ground surface.

Section 5 opens Part 2 and has for its general subject the influence of topography. Chapters 18-25 cover: cold air floods and cold air dams; nocturnal relationships in valleys; cold air winds (down-slope, down-valley, and glacier winds); the sunniness of various slopes; microclimatic effect of various exposures to sunshine; the skin of air on mountain slopes; more on the influence of topography; and concerning the range of validity of meteorological stations. There is also included at the end of this section a supplement on the microclimate of caves. Section 6 is made up of studies of the influence of plant cover: the heat economy of plants and plant temperatures; radiation and temperature relationships in a low plant cover; humidity and wind relationships in a low plant cover; forest meteorology, forest climatology, and stand climate; radiation relationships in an old stand; temperature and humidity relationships in an old stand; wind and precipitation in an old stand; the influence of the makeup of the stand on its climate; the microclimate of circular slashings, clearings, and cuttings; and the climate of the stand border. Section 7, the last, has to do with the relationship of animate creatures including man to the microclimate. The headings of Chapters 36-41 are: the animate world and the microclimate; the unintentional effect of man on the microclimate; the city climate; the conscious modification of the microclimate by man; destructive frost as a microclimatic phenomenon; and the battle against destructive frost. More than 800 references, listed chapter by chapter, are included at the end of the book for those who would trace the studies discussed in the text to their original sources for further information. There is, in addition, an extensive author and subject index.

Geiger's book is an authoritative and welcome text. While this book can be considered a textbook on microclimatology, the methods in microclimatology are only infrequently gone into, and then not in detail. It is doubtless beyond the scope of the present book to dip any further into methodology. Perhaps this points out the need for such a book and it is to be hoped that one will be forthcoming in the near future. Geiger has been credited by Thornthwaite (Presidential Address at the opening meeting of the World Meteorological Organization, Commission for Climatology in Washington, D. C., March 12, 1953) with organizing the field of microclimatology and bringing it into prominence during the last 25 years; and certainly one of the outstanding contributions is the assembling of so much valuable material and information into this notable book. This reviewer highly recommends The Climate near the Ground.

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NOTES AND PERSONALIA

NOTES

New abstract journal in geology--The American Geological Institute will publish an abstract journal covering the publications of its constituent organizations. It will be chiefly a journal of geological abstracts, and the first issue will cover the period January - June, 1953. Thereafter, it is the plan to issue it quarterly. The subscription price will not exceed $2.00 per year. Send word concerning intention to subscribe to the American Geological Institute, 2101 Constitution Ave., Washington 25, D. C.

Fourth Alaskan Science Conference--The Fourth Alaskan Science Conference sponsored by the Alaskan Division of AAAS will be held in Juneau, September 28 to October 2, 1953. Further information may be secured by addressing Dorothy Jean Thompson, P. O. Box 938, College, Alaska.

Eighth Annual Field Conference of Wyoming Geological Association--This Conference will be held at Laramie, July 30 - August 1, 1953. Further information may be secured from the Association, P. O. Box 545, Casper, Wyoming.

Field Conference of the Billings Geological Society--This Conference will be held in north-central Montana in early September. Conference headquarters will be at Zortman. Inquiries should be addressed to J. L. Cramer, Stanolind Oil and Gas Co., 526 Securities Bldg., Billings, Mont.

Symposium on Geochemistry to be held in Zurich, Switzerland, August 10-15, 1953--This Symposium will be held under the auspices of the Section of Inorganic Chemistry of the International Union of Chemistry. There will be two general themes: (1) the problem of organizing geochemical data and making them available, and (2) reports on geochemical research throughout the world. A two-day field excursion will follow the scientific sessions. Further information may be secured from the Secretary, T. F. W. Barth, Geologisk Museum, Oslo 45, Norway, or from the President, Michael Fleischer, U. S. Geological Survey, Washington 25, D. C.

Conference on Radio Meteorology at University of Texas, November 9-12, 1953--This Conference, co-sponsored by a number of groups, will be held at the University in Austin. Further information can be secured from John R. Gerhardt, Box F, University Station, Austin, Texas.

Eleventh Annual Anthracite Conference held at Lehigh University--This Conference, attended by more than 200, was held May 7 and 8, 1953, sponsored jointly by the University and the Anthracite Institute. Papers covered a broad range, from air pollution and its control to new uses for anthracite, anthracite as a source of germanium, and quality control.

PERSONALIA

Philip H. Abelson of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has been designated as the Director of the Geophysical Laboratory of the Institution. He will succeed George W. Morey who has served as Acting Director since the retirement of Leason H. Adams last year.

Hugo Benioff, Professor of Geophysics, California Institute of Technology, has been elected a member of the National Academy of Sciences.

Detlev W. Bronk, President of Johns Hopkins University and of the National Academy of Sciences, has been elected a Corresponding Member of the Académie des Sciences, Paris.

Vladimir P. de Smitt, specialist on trans-oceanic cable problems with Western Union and Associate in Geology at Columbia University, retired at the end of March from the former position.

Milton B. Dobrin, Magnolia Petroleum Co., Dallas, Texas, has been named Editor of Geophysics, publication of the Society of Exploration Geophysicists, for a two-year term.

Karl Dyk, Stanolind Oil and Gas Co., Tulsa, Oklahoma, has been elected Vice President of the Society of Exploration Geophysicists.

Carl Eckart, Director of the Marine Physical Laboratory of the University of California, has been elected a member of the National Academy of Sciences.

George Gamow, Professor of Theoretical Physics, George Washington University, Washington, D. C., has been elected a member of the National Academy of Sciences.

Arthur C. McFarlan, Professor of Geology at the University of Kentucky, has been named as the Distinguished Professor of the Year in the College of Arts and Sciences of the University.

Howard A. Meyerhoff, until recently Administrative Secretary of the American Association for the Advancement of Science, has been named President of the newly organized Scientific Manpower Commission, established through the cooperation of several scientific societies.

John L. Rich, Professor of Geology at the University of Cincinnati, has been named an honorary member of Sigma Gamma Epsilon, national Earth sciences honorary fraternity.

Carl-Gustaf Rossby, Professor of Meteorology at the University of Stockholm, was recently awarded Symons Memorial Gold Medal by the Royal Meteorological Society in London.

J. Frank Schairer of the Geophysical Laboratory of the Carnegie Institution of Washington has been elected a member of the National Academy of Sciences.

Erick O. Schonstedt has left the service of the Naval Ordnance Laboratory and has established the Schonstedt Engineering Company with headquarters in Silver Spring, Maryland. The Company specializes in electromechanical design and development.

David S. Stoner, has undertaken a two-year tour of duty on ground-water development in India with the Technical Cooperation Administration.

Walter D. Sutcliffe, Chief, Section of Field Records, Division of Geodesy, U. S. Coast and Geodetic Survey, has been awarded the Meritorious Service Silver Medal of the Department of Commerce.

F. M. Van Tuyl, Head, Department of Geology, Colorado School of Mines, will retire as Head of the Department in the summer of 1953.

Harry Bouchard, Professor of Geodesy and Surveying at the University of Michigan, died in Washington, D. C., March 21, 1953, at the age of 64. He was born at Michigan City, Indiana, and took his baccalaureate degree from the University of Michigan in 1911. His early professional years were devoted to engineering work for several firms, notably the J. G. White Engineering Co. and the Gardner S. Williams Co. He began his work in teaching at the University of Michigan in 1918, which, except for a three-year tour of duty at Pei Yang University, 1925-1928, continued until his death. He had been a member of AGU since 1938.

William P. Creager, Consulting Hydraulic Engineer of Buffalo, N. Y., died April 4, 1953, at the age of 74. He was born in Baltimore, Md., and took his baccalaureate degree from Rensselaer Polytechnic Institute in 1901. He began his professional career in the service of the Government of the Philippines, then served with the New York State Barge Canal until 1906. He was associated with the J. G. White Engineering Co. from that date until 1922, following which he was Chief Engineer and Vice President of the Northern Utilities and Power Co. until 1931, since which date he had been in consulting work. He was a world authority on hydroelectric development, and author of Engineering for Masonry Dams, coauthor of Hydro-Electric Handbook, and author of many papers and reports. He had been a member of AGU since 1936.

David Thaler, Major in the Air Weather Service of the Air Force, died in Washington, D. C., April 1, 1953, at the age of 37. He was born at Conemaugh, Pa. He studied at Scripps Institution of Oceanography and at New York University, and served in the Air Weather Service from 1943 until his death, devoting his time to weather forecast problems and to climatology. He had been a member of AGU since 1950.

George R. Wait, geophysicist specializing in the study of atmospheric electricity, died April 9, 1953, at the age of 66. He was born at Chase, Kans., took his baccalaureate degree from Kansas State Teachers College in 1914, his Master of Science degree from the University of Iowa in 1917, and his doctorate from the University of Iowa in 1920. Following the receipt of his baccalaureate degree, he devoted two years to high school teaching. In 1920, he entered the service of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington which continued until his retirement in 1951. He was an international authority on the electrical problems of the atmosphere and worked in various parts of the world. Following his retirement, he was called into the service of the Geophysical Directorate of the Air Force Cambridge Research Center as a consultant. He was engaged in this work at the time of his death. He had been a member of AGU since 1929.

Transactions, American Geophysical Union Volume 34, Number 3 June 1953

THIRTY-FOURTH ANNUAL MEETING (1953)

MINUTES, GENERAL ASSEMBLY AND SECTION MEETINGS

EVENING SESSION

The Evening Session of the Thirty-Fourth Annual Meeting was called to order by President Walter H. Bucher at 20h 00m, Monday, May 4, 1953, in the Lecture Room of the National Academy of Sciences, 2101 Constitution Avenue, Washington, D. C. About 230 were in attendance. After preliminary welcoming remarks, President Bucher opened the First Session of the Symposium on the Earth's Interior with introductory comment, and introduced the first speaker, Stanley Keith Runcorn, Assistant Director of Research in Geophysics at Cambridge University, who spoke on The Earth's Core [see abstract in Program, p. 329], showing a cinema of some of their laboratory work and slides of some of the data and results.

Following this address, President Bucher thanked the speaker, and announced the continuation of the Symposium at 09h 00m on the next day, May 5. He then called on Perry Byerly to present the citation of Beno Gutenberg of the Seismological Laboratory, California Institute of Technology, as the Fifteenth Recipient of the William Bowie Medal. President Bucher made the presentation, following which was the response and acceptance of the recipient. The proceedings are set forth on the opening pages [pp.353-355] of this issue.

The session was then adjourned, and was followed by an informal social hour, with refreshments, in the Auditorium.

MORNING SESSION

President Bucher called the Second Session of the Symposium on the Earth's Interior to order at 09h 00m, Tuesday, May 5, 1953, in the Auditorium of the National Academy of Sciences, and proceeded with the discussion of the Runcorn address presented at the First Session. In accordance with the program, formal discussion was presented by E. H. Vestine and Walter M. Elsasser, following which there was a third formal discussion by John W. Graham and informal discussion by L. W. Morley and James R. Balsley, Jr.

Next were presented the addresses of Francis Birch on Elasticity and Constitution of the Earth's Mantle, and of J. Verhoogen on Petrological Evidence on the Temperature Distribution in the Mantle of the Earth [see abstracts in the Program, p. 329]. The formal discussants of these were Harvey Brooks and David T. Griggs. Informal discussants from the floor included Beno Gutenberg, Francis Birch, and Clarence S. Ross. President Bucher closed the Symposium with appropriate comment.

SMOKER

A Smoker was held in the Auditorium of the Cosmos Club on Tuesday, May 5, 1953, starting at 20h 00m. About 240 were in attendance. The gathering was entirely informal, with no program, affording opportunity to renew old acquaintances and make new ones. Full advantage was taken of these opportunities, and there were many lively discussions.

GENERAL ASSEMBLY: LECTURE AND BUSINESS MEETING

The General Assembly was called to order by President Bucher at 14h 05m, Wednesday, May 6, 1953, in the Auditorium of the National Academy of Sciences. About 250 were in attendance. The President introduced Roger Revelle, Director, Scripps Institution of Oceanography, who presented a Preliminary Report on the Capricorn Expedition to the South Pacific [see Program, p. 329, for abstract].

Following the address, there were questions and considerable discussion from the floor. The President then thanked the speaker and called the Business Session to order. The minutes of the last meeting [see Trans., v. 33, pp. 479-481] were approved.

Report of the General Secretary--General Secretary Beij summarized the activities of the Union since the Thirty-Third Annual Meeting. These are reported in connection with the Minutes of the Meetings of the Executive Committee of November 7, 1952 [see Trans., Dec., 1952, pp. 933-942] and May 6, 1953 [to be published in the August, 1953 issue of the Transactions].

A recapitulation of the changes in membership since April 30, 1952, is as follows:

Membership, April 30, 1953	4775	
New members, May 1, 1952 to May 1, 1953	606	
Reactivated	12	5393
Resignations	111	
Deceased	23	
Dropped	249	
Inactive	10	393
Membership, May 1, 1953		5000

Reports of Standing Committees

Meetings--Chairman John Putnam Marble of the Committee on Meetings announced the dates for the Thirty-Fifth Annual Meeting as May 3-5, 1954.

Reports of other Standing Committees were not presented, and will be published in the Transactions.

Reports of Special Committees

Resolutions--Chairman Mary C. Rabbitt presented six resolutions, which were unanimously adopted, as follows:

(1) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The National Academy of Sciences and the United States Public Buildings Administration have provided the use of meeting rooms and other services for the Thirty-Fourth Annual Meeting of the American Geophysical Union without cost to the Union, therefore be it

RESOLVED, That the American Geophysical Union expresses its great appreciation of this cooperation, extended over many years, and instructs the General Secretary to express the thanks of the Union to the appropriate officials.

(2) RESOLUTION OF THANKS TO STANFORD UNIVERSITY

WHEREAS, Stanford University generously provided space and other facilities which greatly contributed to the success of the Twenty-Ninth Regional Meeting at Palo Alto, California, February 6-7, 1953, therefore be it

RESOLVED, That the American Geophysical Union extends its thanks to Stanford University, and instructs the General Secretary to forward a copy of this resolution to President J. Wallace Sterling.

(3) RESOLUTION OF THANKS TO THE CARNEGIE INSTITUTION OF WASHINGTON

WHEREAS, The Carnegie Institution of Washington has for many years provided office space for the American Geophysical Union, without which the Union could not adequately function, therefore be it

RESOLVED, That the American Geophysical Union expresses its deep appreciation of this continued assistance and instructs the General Secretary to express this appreciation to the appropriate officers of the Carnegie Institution of Washington.

(4) RESOLUTION ON COMMUNICATIONS SERVICES

WHEREAS, The Secretary of Commerce, in cooperation with the Foreign Service of the United States, the officers of the Foreign Service, and Foreign Service Operations Division of the Office of International Trade, have made available their special telegraphic facilities for transmitting teleseismic data to the United States Coast and Geodetic Survey, and

WHEREAS, The data have greatly enhanced the earthquake location program of that Survey, and

WHEREAS, The data have been made available by the Survey to seismologists throughout the world to aid in the more thorough analysis of their records, therefore be it

RESOLVED, That the American Geophysical Union expresses its appreciation for this valuable contribution to seismological research, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of Commerce, the

Director General of the Foreign Service of the United States, the Foreign Service Operations Division of the Office of International Trade, and officers of the Foreign Service at the following stations: Djakarta, Java; Bombay, India; Brisbane, Australia; Copenhagen, Denmark; Guatemala City, Guatemala; Lima, Peru; Malaga, Spain; Mexico City, Mexico; Perth, Australia; Rome, Italy; Santiago, Chile; Strasbourg, France; Sydney, Australia; Tananarive, Madagascar; Pretoria, Union of South Africa; Wellington, New Zealand; and Dublin, Ireland.

(5) RESOLUTION ON TIME-SIGNAL SERVICE

WHEREAS, There is a vital need in all seismological work for accurate time service, and

WHEREAS, The time service maintained by the United States Naval Observatory, the Naval Communications Service, and the National Bureau of Standards has been of great use in this work, therefore be it

RESOLVED, That the American Geophysical Union expresses its appreciation of the valuable scientific cooperation and reiterates its desire for the continuance of this time-signal service, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, the Director of Naval Communications, the Superintendent of the Naval Observatory, the Secretary of Commerce, and the Director of the National Bureau of Standards.

(6) RESOLUTION ON SCIENCE IN GOVERNMENT

WHEREAS, It is of great importance to our country and to science that the work in its scientific agencies be carried on with both efficiency and integrity, be it

RESOLVED, That the American Geophysical Union believes that government scientific organizations should be staffed by high-caliber scientists, that these scientists should be permitted to conduct and report their investigations with scientific objectivity, and that the American Geophysical Union is opposed to all attempts to interfere with the work of scientific agencies for other than scientific motives.

Tellers--(It was the intention to announce at this time the results of the election of officers of the Union for the triennium beginning July 1, 1953, but this was overlooked.) Chairman Earl Ingerson reported concerning the election held by mail ballot during March, 1953. The Committee met on April 14, 1953, and tabulated the ballots as follows (the reports of Section elections were presented before the respective Sections, but are combined here for ready reference):

Total number of ballots received		1888
Rejected ballots		
Ballots without identification	3	
Ballots mailed and received late	4	
Ballots from non-citizens of the United States	12	19
Qualified ballots tabulated		1869

The following officers were elected for the triennium July 1, 1953 to June 30, 1956:

Officers of the Union

President	James B. Macelwane
Vice President	Maurice Ewing
General Secretary	John Putnam Marble

Section of Geodesy

President	Albert J Hoskinson
Vice President	Milton O. Schmidt
Secretary	Frank L. Culley

Section of Oceanography

President	Richard H. Fleming
Vice President	Walter H. Munk
Secretary	Donald W. Pritchard

Section of Seismology

President	Ross R. Heinrich
Vice President	Hugo Benioff
Secretary	James A. Peoples, Jr.

Section of Volcanology

President	William F. Foshag
Vice President	Gordon A. Macdonald
Secretary	Felix Chayes

Section of Meteorology

President	Phil E. Church
Vice President	Jerome Namias
Secretary	Woodrow C. Jacobs

Section of Hydrology

President	Harold G. Wilm
Vice President	Ray K. Linsley
Secretary	Harry F. Blaney

Section of Terrestrial Magnetism and Electricity

President	Victor Vacquier
Vice President	H. R. Joesting
Secretary	L. R. Alldredge

Section of Tectonophysics

President	Francis Birch
Vice President	L. B. Slichter
Secretary	James T. Wilson

Members of Section's Executive Committee: Wilbur S. Burbank and Thomas P. Thayer

Pacific Southwest Regional Committee

(To organize and select its own officers under the temporary chairmanship of the present Regional Chairman, J. W. Johnson)

R. C. Counts, Jr., H. H. Engelbrecht, M. R. Huberty, H. McV. Stafford, Vito A. Vanoni, and C. F. Woffinden.

[The Special Committee of Tellers, appointed by President Bucher upon nomination of the Section officers, was as follows: Earl Ingerson (Chairman); Geodesy--L. E. Shmidl, Rex Finley, and A. C. Poling; Seismology--Beauregard Perkins, Benjamin L. Snavely, and Howard Tatel; Meteorology--Wm. L. Molo, John H. Thomas, and P. R. Stinchfield; Terrestrial Magnetism and Electricity--R. E. Gebhardt, H. F. Johnston, and E. O. Schonstedt; Oceanography--Harry S. Ladd, B. K. Couper, and Gordon Lill; Volcanology--Norman Herz, George Switzer, and H. S. Yoder; Hydrology--W. D. Potter, Ralph N. Wilson, and Morgan D. Dubrow; Tectonophysics--K. E. Lohman, G. H. Espenshade, and Donald C. Duncan.]

General Secretary Beij reminded those present that the Tenth General Assembly of the International Union of Geodesy and Geophysics will be held in Rome, Italy, September 15-29, 1954, and that it is not too early to begin considering delegates, scientific papers and reports, etc., for this Assembly.

The meeting adjourned at 16h 35m.

K. HILDING BEIJ, General Secretary
WALDO E. SMITH, Executive Secretary

APPENDIX A--MINUTES OF THE ANNUAL MEETING OF 1953, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

President Hess called the meeting to order in the Lecture Room of the National Academy of Sciences at 09h 13m on May 4, 1953. There being no objection from the floor, and no corrections received, the President declared the minutes of the 1952 meeting approved as published in the Transactions [v. 33, pp. 481-482, 1952].

L. E. Shmidl announced the newly elected officers of the Section of Geodesy for the forthcoming triennium [see Tellers' report on preceeding page].

There being no further business to transact, the scientific session began with an announcement by Erwin Schmid about preliminary values of the ellipsoid obtained by using deflections of the vertical, based on the North American 1927 datum, in Hayford's computations. The session then proceeded as published in the Program [p. 323].

Papers by Arthur S. G. Grant, John C. Duecker, and C. H. Ney, who could not be present, were read by E. J. Parkin, B. F. Howell, and A. D. Sollins, respectively. Papers by Stephan Thyssen-Bornemisza and Manuel Medina were presented by title.

Approximately 90 members and guests attended the meeting.

The meeting adjourned at 11h 30m.

FRANK L. CULLEY, Secretary

APPENDIX B--MINUTES OF THE ANNUAL MEETING OF 1953, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Thirty-Fourth Annual Meeting of the Section of Seismology was held May 6, 1953, in the Lecture Room, National Academy of Sciences, Washington, D. C. The session was called to order at 09h 00m by President Byerly. The minutes of the 1952 meeting were approved as published in the Transactions [v. 33, p. 482, 1952].

Beauregard Perkins, one of the Section's representatives on the Union's Committee of Tellers, reported the results of the elections for the triennium 1953-56 [see Tellers' report on page 504].

L. M. Murphy presented two resolutions for action by the Section. These were approved and forwarded to the Union [see Resolutions (4) and (5) in the Minutes of the Business Meeting of the Union].

As there was no further business, the Business Session was adjourned and was followed immediately by the Scientific Session shown on the Program [see p. 323].

JAMES T. WILSON, Secretary

APPENDIX C--MINUTES OF THE ANNUAL MEETING OF 1953, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Thirty-Fourth Annual Meeting of the Section of Meteorology was held May 4, 1953, in the Auditoria of the General Services Building and the National Academy of Sciences. It is estimated that around 200 members and guests attended the two sessions of the Section.

The business session was opened at 09h 00m by Secretary Woodrow C. Jacobs, presiding in the absence of President Benjamin Holzman. As the first item of business the chairman of the Committee of Tellers, William J. Molo, reported the results of the election of new Section officers for the period 1953-1956 [see Tellers' report, p. 504].

The Secretary at this point turned the meeting over to Phil E. Church, the newly elected President of the Section.

Since no corrections were received, the Chairman declared the minutes of the Thirty-Third Annual Meeting of the Section of Meteorology approved as published in the Transactions [v. 33, pp. 482-483, 1952]. The Chairman then appointed a Committee on Resolutions (Charles S. Gilman, Chairman, R. Hanson Weightman, and Alfred H. Woodcock).

A brief report was given by the Meteorological Editor, Charles S. Gilman. The reports of the Committees on Cloud Physics, Atmospheric Diffusion, Problems of the Upper Atmosphere, and Climatology were read by title.

The following two resolutions, presented by Charles F. Brooks and Charles S. Gilman, respectively, were approved by vote of the Section.

(1) It is Resolved that a Joint Committee on the Interrelations between Meteorology and Oceanography be appointed by the Presidents of the Sections of Meteorology and Oceanography and by the Council of the American Meteorological Society.

(2) It is Resolved that the President of the Section appoint an ad hoc committee to survey and make recommendations concerning the activities of the Meteorological Section as related to those of other meteorological societies.

The Business Meeting was adjourned at 09h 30m and immediately followed by the schedule of scientific papers as shown in the program [pp. 323-324].

WOODROW C. JACOBS, Secretary

APPENDIX D--MINUTES OF THE ANNUAL MEETING OF 1953, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Thirty-Fourth Annual Meeting of the Section of Terrestrial Magnetism and Electricity of the American Geophysical Union was held on May 5 and 6, 1953. The first session was called to order at 14h 07m on Tuesday, May 5, in the Auditorium of the General Services Administration Building by President J. Wallace Joyce. There were approximately 70 members and guests in attendance. The minutes of the previous meeting were approved as published in the Transactions [v. 33, p. 482; June, 1952]. R. E. Gebhardt, Chairman of the Committee of Tellers of our Section, announced the successful candidates for the triennium, July 1, 1953 to June 30, 1956 [see Tellers' report, p. 505].

President Joyce gave a very brief account of preparations which are being made for the Third International Geophysical Year to be held in 1957-58.

After routine announcements the scientific program was begun in accordance with the program [see p. 324]. Paper (6) was read by E. H. Vestine in the absence of the authors. The session adjourned at 16h 00m.

The second session was convened at 09h 11m on May 6 in the Auditorium of the National Academy of Sciences. After routine announcements the technical program was given as published except that papers (10), (11), and (17) were read by C. T. Elvey in the absence of the authors and paper (14) was read by title only because of the absence of the author. The meeting was adjourned at 11h 08m.

L. R. ALLDREDGE, Secretary

APPENDIX E--MINUTES OF THE ANNUAL MEETING OF 1953, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Thirty-Fourth Annual Meeting of the Section of Oceanography was held in Washington, May 5 and 6, 1953. The first session convened at 09h 00m in the Lecture Room of the National Academy of Sciences and adjourned at 12h 30m. The second session met at 09h 00m on May 6, in the Auditorium of the General Services Building and adjourned at 13h 00m. President A. C. Redfield presided at both sessions.

As no corrections were offered to the minutes of the previous Annual Meeting published in the Transactions [v. 33, p. 483, June, 1952], they were approved.

The President announced the election of the following officers of the Section to serve for the period July 1, 1953 to June 30, 1956: President, Richard H. Fleming; Vice-President, Walter H. Munk; and Secretary, Donald W. Pritchard.

The following motion was made, seconded, and passed by the Section: "A joint committee on the interrelations between meteorology and oceanography shall be appointed by the Presidents of the Sections of Meteorology and Oceanography of the American Geophysical Union and by the Council of the American Meteorological Society."

The scientific program of the two sessions consisted of the presentation and discussion of the papers listed in the Program [see p. 325]. Changes in the program were as follows: Papers (1), (2), (3), (11), and (21) were read by title. Two additional papers were presented at the first session:

(22a) CHARLES COX and WALTER H. MUNK: Measurement of the roughness of the sea surface from photographs of the Sun's glitter
(22b) GORDON GROVES: Ocean waves of supertidal period

The following additional papers were presented by title only:

(22c) WILLIAM S. VON ARX and W. S. RICHARDSON: The surface outcrop of the Gulf Stream front
(22d) ROGER REVELLE and WILLARD N. BASCOM: A deep-sea instrument station
(22e) ROGER REVELLE and WILLARD N. BASCOM: Free-diving: A new exploratory tool

RICHARD H. FLEMING, Secretary

APPENDIX F--MINUTES OF THE ANNUAL MEETING OF 1953, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

President Larsen called the meeting to order at 14h 00m, May 4, 1953. N. Herz, Chairman of the Section's Committee of Tellers, reported on the newly elected officers of the Section for the triennium 1953-56 [see Tellers' report on p. 504].

The Secretary urgently requested more effective cooperation from members in arranging the Annual Program; of the 23 authors responsible for the papers listed on the program, only two are members of the Section. One of these volunteered his contribution several days after the deadline for abstracts and titles had passed; the other is co-author of an invited paper. Invitations amounting to requests were sent to more than 20 members of the Section by personal letter almost four months before the meeting.

There was no other business. The scientific program [see pp. 325-326] got under way at 14h 20m and the meeting adjourned at 17h 00m.

FELIX CHAYES, Secretary

APPENDIX G--MINUTES OF THE ANNUAL MEETING OF 1953, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

President Frank J. Veihmeyer called the Annual Meeting to order at 09h 00m, May 4, 1953, and presented the following report:

> The officers of the Section are completing their term of office for the present triennium largely with this meeting. The new officers of the Section who will be announced shortly will begin to function in the near future. The best wishes of the present officers of the Section go to the new officials.
>
> I want to take this opportunity to express the thanks of the Section to the members of the permanent committees of the Section. Knowing that the work of the committee largely depends upon the chairman, particular thanks are due them. They are as follows: W. W. Hastings, J. W. Johnson, A. R. Croft, William O. Field, Joseph F. Poland, L. L. Harrold, Jack L. Hough, H. V. Peterson, G. B. Bodman, William C. Ackermann, Carl F. Izzard, and Forrest L. Rhodes.
>
> The above members of the permanent research committees also comprise the Committees on Nominations and on Honor and Awards under the chairmanships of W. C. Ackermann and C. F. Izzard, respectively.
>
> The Executive Committee of the Section, as most of you know, is as follows: F. J. Veihmeyer, Walter B. Langbein, Ray K. Linsley, Morgan D. Dubrow, Lorenz G. Straub, Ralph N. Wilson, and Walter T. Wilson.
>
> We are particularly indebted to Ralph N. Wilson, who has been responsible for the programs of the Section meetings here in Washington. I know that this has entailed a large amount of work, and the quality of the programs shows what a fine job he has done.
>
> The Section of Hydrology has held a number of regional meetings. My contact has been largely through the meetings of the Pacific Southwest Region. I believe that these regional meetings serve a very worthwhile purpose, not only because of the papers presented at them and the information gotten by members of the Union who attend them, but because they afford the only means of contact with the union. It is a way of getting down to the grass roots. Most of our members who are interested in hydrology are in the western part of the country, and many of them never have the opportunity of coming to Washington. Therefore, if it were not for the regional meetings they would lose contact with the Union. I would like to take this opportunity to call the attention of the members of our Section to the need for strengthening these meetings. In the Pacific Southwest Region only two Sections have participated during the last two years, Hydrology and Meteorology. If other Sections would take part, I am sure the value of the meetings would be greatly increased. It would take no greater effort on the part of the organization committee to arrange for a large program for several sections than it does for the two which now meet. The next meeting of the Pacific Southwest Region probably will be held in Los Angeles at the University of Southern California, though plans have not been definitely made.
>
> I want to also thank the Pacific Southwest Regional Committee for the fine work they have done. This Committee during the present triennium was headed by J. W. Johnson.
>
> Lastly I want to thank Walter Langbein for the many times he has substituted for me when I could not be in Washington and for the excellent advice and help he has been to me during the past three years. I also appreciate very much the help Ray Linsley has given me and the services he has rendered to the Section as Secretary.

President Veihmeyer briefed a report prepared by Secretary Ray K. Linsley, and stated that the East Central Region held a very successful Regional Meeting at Chicago in September, 1952, in conjunction with the Centennial of Engineering. The Pacific Southwest Region held its annual meeting at Stanford University in February, 1953. Attendance at these meetings has always been good and those present have indicated an enthusiastic approval of the meetings. The officers of the Section are anxious to encourage additional meetings in other regions. Persons interested in regional activity in their area are urged to contact the Section officers. The next regular meeting of the International Association of Hydrology will be held in Rome, Italy, in late summer of 1954. Further information concerning this meeting will be published in the Transactions as soon as it becomes available.

William D. Potter announced the newly elected officers for the Section for the 1953-1956 triennium [see Tellers' report, p. 504].

Carl F. Izzard, Chairman of the Committee on Honors and Awards, stated that as a result of a survey of the Hydrology papers published in the Transactions of 1951, the Committee felt that two papers were exceptionally good and that they warranted awards. The papers are as follows:

(a) Best Paper of the Year (for an outstanding original contribution to scientific hydrology), "Seepage into drain tubes in stratified soil," by Don Kirkham.

(b) Junior Award (for the first paper of authors who have received their baccalaureate degree not more than ten years prior to submission of the paper), " A comparison of several heat and mass transfer networks of interest in water conservation," by Heinz F. Poppendiek and Myron Tribus.

There being no further business the technical session proceeded according to the Program [see pp. 326-327] except for the following:

(R2) Report by Hough was presented by title.
(R3) Report by Croft was presented by title.
(R5) Report by Rhodes was presented by R. N. Wilson.

The session adjourned at 12h 00m.

The afternoon session of May 4 was called to order by Chairman H. G. Wilm at 14h 00m. The Program was followed with the exceptions noted below:

(R6) Report by Johnson was presented by title.
(7) Paper by Shulits was presented by M. A. Mason.
(R7) Report by Field was presented by title.

Two papers, not on the printed Program, were presented following the Glacier papers:

(a) ARTHUR JOHNSON: Nisqually Glacier Observations, 1857 - 1952.
(b) A. E. HARRISON: Minor Advances of the Nisqually Glacier, Mt. Rainier, Washington (Presentation by Arthur Johnson).

The meeting adjourned at 17h 00m.

Chairman Franklin F. Snyder called the morning session of May 5 together at 09h 05m. The Program was followed with exception that paper (23) by Madow was presented by W. T. Wilson.

The Session adjourned at 12h 10m.

The final session was called to order at 14h 00m by Chairman H. V. Peterson. The session conformed with the Program except as follows:

(26) Paper by Schumm was presented by Richard Chorley.
(29) Paper by Fletcher, Harris, Peterson, and Chandler was presented by L. L. Harrold.
(30) Paper by Huberty was presented by F. J. Veihmeyer.
(32) Paper by Zingg was presented by T. W. Edminster.

The meeting adjourned at 16h 40m.

RALPH N. WILSON, Acting Secretary

APPENDIX H--MINUTES OF THE ANNUAL MEETING OF 1953, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The annual Meeting of the Section of Tectonophysics was called to order by President Robert Balk at 14h 00m, May 5, 1953, in the Lecture Room of the National Academy of Sciences. There were no committee reports. Kenneth E. Lohman announced the newly elected officers of the Section for the next three years [see Tellers' report on p. 505].

The technical session followed and this conformed to the published Program, page 327 of the Transactions of 1953, except that papers numbered (6) and (7) were reversed in order of presentation. The meeting adjourned at 16h 55m.

WILBUR S. BURBANK, Secretary

PACIFIC SOUTHWEST MEETING, FEBRUARY 6-7, 1953

The Pacific Southwest Regional Meeting was held at Stanford University on February 6-7, 1953 with the sections of hydrology and meteorology participating. A total of 31 papers were presented before a registered attendance of about 140. An exhibit of equipment by Fisher Scientific Co., A. Lietz and Co., Leupold and Stevens, General Electric, Pacific Pump, Peerless Pump, Stacey's Bookstore, and Stanford Research Institute attracted considerable interest. A tour of the Stanford Hydraulic Laboratory, the billion-volt linear accelerator, and the Stanford Research Institute concluded the program.

DAVID K. TODD, Program Chairman

SPECIAL ANNOUNCEMENTS

Regional Meeting in Minneapolis, Minnesota, August 31, 1953--This is the final announcement concerning the Thirtieth Regional Meeting [see also April, 1953, p. 313, Feb., 1953, p. 157, etc.] to be held in Minneapolis, August 31, 1953. A provisional program is available. A copy may be secured through the Chairman of the Regional Committee (Martin E. Nelson, U. S. Engineer Office, Post Office Bldg., St. Paul, Minn.).

Pacific Southwest Regional Meeting--Pending the organization of the newly elected Regional Committee [see p. 505, this issue], dates for the Annual Meeting in this Region are tentatively January 29-30, 1954. Informal word indicates that tentative plans have been made to hold the meeting at the University of Southern California under the joint sponsorship of the Geology and Civil Engineering Departments, with arrangements at the University to be handled by John Mann and Stanley Butler. Those interested should get into touch with one of these, a member of the new Committee, or the Chairman (J. W. Johnson) of the old Committee.

Thirty-Fifth Annual Meeting to be held May 3-5, 1954--The Thirty-Fifth Annual Meeting of AGU will be held in Washington, D. C., May 3-5 (Monday-Wednesday), 1954. This is a first call for titles and abstracts of papers, and any suggestions you may have for symposia or other matter relating to the Meeting. Address your response to the office of AGU or to the appropriate newly elected Section secretary [see pp. 504-505, this issue]. Watch SPECIAL ANNOUNCEMENTS for further information.

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TRANSACTIONS
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STRENGTH OF FIGURE FOR TRILATERATION

Chi-san Shu

Abstract--An investigation of five figures commonly used in shoran trilateration resulted in numerical values expressing the relative accuracies obtainable using these figures. Triangles and quadrilaterals are examined for various shapes, while the semi-hexagon, hexagon, and square are examined fixed in shape but with different locations for the fixed lines.

Introduction--Shoran, an electronic method of measuring distances from 100 to 400 miles in length developed during World War II may be used to extend horizontal control quickly over large areas where conventional triangulation methods are impossible. In shoran survey nets, all the sides are measured instead of the angles; therefore, the nets are called trilateration nets.

The term "strength of figure" is applied to a function used to determine the strongest route through a chain of triangulation figures composed of quadrilaterals and central-point polygons. The shape of the figures determines the manner in which angular errors affect the computed lengths and positions.

The shape of the figures used in a trilateration scheme also determines the manner in which errors of the measured distances affect the positions of the new stations. In this paper the effect of shape changes of triangles and equal-sided quadrilaterals on the positions of new stations is investigated, as is the effect of the location of the fixed line on the positions of new stations in semi-hexagonal, hexagonal, and square networks. By the use of least squares and the theory of errors, the reciprocal weights of the mean-square error of the positions of new stations can be found.

The error of the position of a new station is directly proportional to the square root of the reciprocal weight of that station. The relative strength, therefore, can be obtained by a simple comparison of the numerical values of the square roots of the various reciprocal weights. The figure having the smallest value will be strongest.

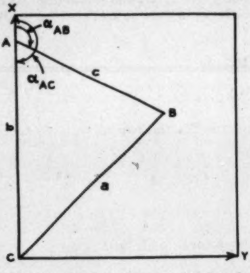

Fig. 1--Single triangle, AC fixed

c

Conventional figures and their strengths--(1) The basic figure of trilateration is a triangle with one side fixed in length and direction, while the other two sides of the triangle are measured. The triangle shown in Figure 1 has AC (=b) fixed in the X-direction of the coordinate system. The third vertex B can be determined by measuring the distances AB (=c) and CB (=a) by shoran. If we assume that the measured sides, AB and CB, have the same constant error irrespective of their lengths, the error in position B will then depend upon the value of angle A and upon the ratio c to b.

The 64 figures obtained by setting angle A equal to 30°, 45°, 60°, 75°, 90°, 105°, 120°, and 135°, and for each of these values choosing eight different ratios of c to b (0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, and 2.0), are now examined.

The formula for the mean position error of station B is derived by the following steps. In triangle ABC of Figure 1, the law of cosines gives

$$a^2 = b^2 + c^2 - 2bc \cos A \qquad (1)$$

The variations of a, c, and A result from total differentiation of (1), with b constant. Thus

$$c \sin A \, dA = (a\,da - c\,dc)/b + \cos A \, dc \qquad (2)$$

The coordinates, X_B and Y_B, of station B are given by the expressions

$$X_B - X_A = c \cos \alpha_{AB} \quad \text{(3)}$$

$$Y_B - Y_A = c \sin \alpha_{AB} \quad \text{(4)}$$

Since X_A is fixed, (3) becomes upon differentiation

$$d\,X_B = -\,c \sin \alpha_{AB}\, d\alpha_{AB} + \cos \alpha_{AB}\, dc \quad \text{(5)}$$

Now $\alpha_{AB} = 180° - A$, $d\,\alpha_{AB} = -\,dA$, $\sin \alpha_{AB} = \sin A$, $\cos \alpha_{AB} = -\cos A$, so (5) becomes

$$d\,X_B = c \sin A\, dA - \cos A\, dc \quad \text{(6)}$$

Substituting (2) into (6), we have

$$d\,X_B = (a da - c dc)/b \quad \text{(7)}$$

Similarly, (4) after differentiation and substitution from (2) becomes

$$d\,Y_B = (a da - c dc) \cot A/b + \csc A\, dc \quad \text{(8)}$$

Consequently substituting (7) into (8),

$$d\,Y_B = (\cos A\, d\,X_B + dc)/\sin A \quad \text{(9)}$$

The values of cos A and sin A can be obtained from (1)

$$\cos A = (b^2 + c^2 - a^2)/(2\,bc) \quad \text{(10)}$$

$$\sin A = \sqrt{[(b + c)^2 - a^2]\,[-\,(b - c)^2 + a^2]}/(2\,bc) \quad \text{(11)}$$

Substituting (7), (10), and (11) into (9), we obtain

$$d\,Y_B = [a\,(b^2 + c^2 - a^2)\,da + c\,(b^2 - c^2 + a^2)\,dc]/b\,\sqrt{[(b + c)^2 - a^2]\,[-\,(b - c)^2 + a^2]} \quad \text{(12)}$$

Let us assume that the mean-square errors of the lengths a and c are each equal to M; then M_X, the mean-square error of station B in the direction of the X-axis, can be derived from (7) by the law of error propagation

$$M_X{}^2 = [(a^2 + c^2)/b^2]\, m^2 = (1/P_X)\, m^2 \quad \text{(13)}$$

where $1/P_X$ designates the reciprocal weight at station B in the direction of the X-axis.

Similarly, M_Y, the mean-square error of station B along the Y-axis, can be derived from (12). We have

$$\begin{aligned} M_Y{}^2 &= m^2\, [a^2\,(b^2 + c^2 - a^2)^2 + c^2\,(b^2 - c^2 + a^2)^2]/\left\{b^2\,[(b + c)^2 - a^2]\,[-\,(b - c)^2 + a^2]\right\} \\ &= (1/P_Y)\, m^2 \quad \text{(14)} \end{aligned}$$

where $1/P_Y$ designates the reciprocal weight at station B in the direction of the Y axis.

Then M, the mean position error for station B, can be derived from (13) and (14), since $M^2 = M_X{}^2 + M_Y{}^2$. After some reductions we arrive at

$$M^2 = m^2 (8\,a^2c^2)/[4\,b^2c^2 - (a^2 - b^2 - c^2)^2] = m^2[(1/P_X) + (1/P_Y)] \quad \text{(15)}$$

by which M is given as a function of the lengths a, b, and c. Triangles of different shapes give different numerical values for M, even though the errors of line measurement remain the same. We take M/m to be the strength of figure. The smaller the numerical value of this ratio, the greater is the strength, since we will then have a smaller position error, M, for station B. The strengths for station B obtained with certain values of angle A and for a number of ratios of sides c to b are given in Table 1.

Table 1--Relative strength of figure in the shoran triangle

Angle A	Ratio of sides c to b							
	2.00	1.75	1.50	1.25	1.00	0.75	0.50	0.25
°								
30	3.51	2.87	2.28	1.78	1.46	1.45	1.75	2.24
45	2.95	2.52	2.12	1.78	1.53	1.42	1.47	1.68
60	2.83	2.48	2.16	1.87	1.63	1.47	1.41	1.47
75	2.92	2.60	2.30	2.03	1.78	1.59	1.46	1.41
90	3.16	2.85	2.55	2.26	2.00	1.77	1.58	1.46
105	3.60	3.26	2.94	2.62	2.32	2.04	1.80	1.60
120	4.32	3.94	3.56	3.19	2.83	2.48	2.16	1.87
135	5.60	5.11	4.64	4.16	3.70	3.24	2.80	2.38

(2) The quadrilateral is the figure in general use in the United States for triangulation. In this paper only the equal-sided quadrilateral or rhombus will be considered. In Figure 2, the angles, A, B, C, and D and the lengths of the diagonals will be varied to change the shape of the quadrilateral. Two of the four stations are fixed; the positions of the two new stations are determined by shoran. The strength for a given shape is determined by a comparison of the square roots of the reciprocal weights for the new stations.

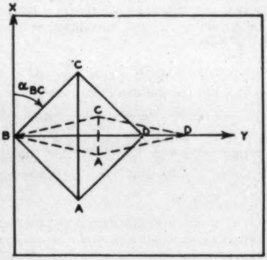

Fig. 2--Quadrilateral, AB fixed

Because the new stations are not determined by a simple two-line intersection, the problem may best be solved by least squares. The reciprocal weights of the positions of different stations are then a by-product of the adjustment of the net. Assume that the length of line BC is S_{BC}, the coordinates of B and C are X_B, Y_B, and X_C, Y_C, respectively, and the azimuth of BC is α_{BC}. Then

$$S_{BC}^2 = (X_C - X_B)^2 + (Y_C - Y_B)^2 \; . \; . \; . \quad (16)$$

Differentiating and inserting $\sin \alpha_{BC}$ and $\cos \alpha_{BC}$

$$dS_{BC} = \cos \alpha_{BC}\, dX_C - \cos \alpha_{BC}\, dX_B + \sin \alpha_{BC}\, dY_C - \sin \alpha_{BC}\, dY_B \; . \; . \; . \quad (17)$$

Since every line on the quadrilateral has an equation of the form (17), we can apply (17) to any line after a suitable change in subscfipt. We assume that dS_{BC} is a correction to be added to $(S_{BC})_o$ to obtain the true length, or better, the most probable length. $(S_{BC})_o$ is a computed length based upon the approximate values of the coordinates for points B and C. On the other hand, the measured shoran length between points B and C is S'_{BC}, which in comparison with the true or the most probable length $(S_{BC})_o + dS_{BC}$ has a discrepancy v_{BC}. Thus

$$v_{BC} = (S_{BC})_o + dS_{BC} - S'_{BC} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (18)$$

Substitute (17) into (18) and set $(S_{BC})_o - S'_{BC} = -L_{BC}$ so that (18) becomes

$$v_{BC} = \cos \alpha_{BC}\, dX_C - \cos \alpha_{BC}\, dX_B + \sin \alpha_{BC}\, dY_C - \sin \alpha_{BC}\, dY_B - L_{BC} \; . \; . \; . \; . \quad (19)$$

Equation (19) is the error equation for a line between points B and C. The five error equations for the five measured lines of the quadrilateral constitute the family of error equations, in which dX_A, dY_A, dX_B, and dY_B are each zero, since AB is fixed. After setting $\cos \alpha_{BC} = a_{BC}$ and $\sin \alpha_{BC} = b_{BC}$, etc., we have

$$\left.\begin{array}{llll} v_{BC} = & a_{BC}dX_C + b_{BC}dY_C & & - L_{BC} \\ v_{BD} = & & c_{BD}dX_D + d_{BD}dY_D & - L_{BD} \\ v_{CD} = & - a_{CD}dX_C - b_{CD}dY_C & + c_{CD}dX_D + d_{CD}dY_D & - L_{CD} \\ v_{CA} = & - a_{CA}dX_C - b_{CA}dY_C & & - L_{CA} \\ v_{AD} = & & c_{AD}dX_D + d_{AD}dY_D & - L_{AD} \end{array}\right\} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (20)$$

The normal equations are then

$$\left.\begin{aligned}
(aa)dX_C + (ab)dY_C + (ac)dX_D + (ad)dY_D - (aL) = 0\\
(ab)dX_C + (bb)dY_C + (bc)dX_D + (bd)dY_D - (bL) = 0\\
(ac)dX_C + (bc)dY_C + (cc)dX_D + (cd)dY_D - (cL) = 0\\
(ad)dX_C + (bd)dY_C + (cd)dX_D + (dd)dY_D - (dL) = 0
\end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots \quad (21)$$

The reciprocal weights for X_C, Y_C, X_D, and Y_D, namely, $Q_{1.1}$, $Q_{2.2}$, $Q_{3.3}$, and $Q_{4.4}$ respectively, are obtained from the solution of the normal equations.

According to the theory of the error ellipse, the mean position errors, M_C and M_D, for stations C and D can be obtained as

$$\left.\begin{aligned}
M_C{}^2 = M^2_{max} + M^2_{min} = M_X{}^2 + M_Y{}^2 = (Q_{1.1} + Q_{2.2})m^2\\
M_D{}^2 = (Q_{3.3} + Q_{4.4})m^2
\end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots \quad (22)$$

Here, M_{max} and M_{min} are position errors along the major and minor axes of the error ellipse, whereas M_X and M_Y are the position errors in the directions of the coordinate axes. As before, m is the mean-square error of the measured length of unit weight. The mean position error at a station, although a satisfactory indicator for our purposes, is not an exact measure of the error because the real position error varies with direction. The trace of the errors around a station is almost elliptical; strictly speaking, it is a kidney-shaped curve with only the maximum and minimum errors in coincidence with the major and minor axes of the ellipse.

The problem was to find the distribution of relative strength among the new stations in a shoran survey network. For the quadrilateral, the answer is given by the square roots of the quantities in the parentheses on the right sides of (22).

Computations were made for quadrilaterals in which line AB was fixed and angle CBA was given the successive values 135°, 120°, 105°, 90°, 75°, 60°, and 45°. The strengths for new stations C and D corresponding to the assigned shapes are given in Table 2. The smaller the numerical value in Table 2, the greater is the strength of the position.

Table 2--Strengths at stations C and D in a quadrilateral

Case	Angle B	Strength for Station C	Strength for Station D
1	135°	2.45	1.41
2	120	2.00	1.45
3	105	1.75	1.51
4	90	1.60	1.60
5	75	1.51	1.75
6	60	1.45	2.00
7	45	1.41	2.45

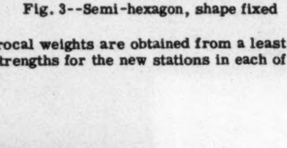

Fig. 3--Semi-hexagon, shape fixed

(3) For more complicated networks, consideration is restricted to variations in relative strength for new stations according to the location of the fixed line within the network.

The semi-hexagon is a network composed of a quadrilateral and a triangle as shown in Figure 3. It may also be thought of as a five-station figure composed of two equal-sided overlapped quadrilaterals.

With the shape of the semi-hexagon fixed, the fixed line is taken to be AB, BC, BE, AC, and AE in turn, each choice yielding a set of values for the strengths of the new stations. By symmetry these five choices will suffice for all of the nine possible locations.

Since there are eight measured lines, we will have eight error equations similar to (19). These will involve only six differential coordinates because the four differential coordinates for the two ends of the fixed line will vanish.

Proceeding as for the quadrilateral the reciprocal weights are obtained from a least-squares solution of the eight observation equations. The strengths for the new stations in each of the five cases are given in Table 3, in which, as

Table 3--Strengths of new stations in a semi-hexagon

Case	Fixed line	Station				
		A	B	C	D	E
1	AB	. . .	. . .	1.75	2.74	1.41
2	BC	1.91	. . .	. . .	1.91	1.33
3	AC	. . .	1.25	. . .	1.88	1.33
4	BE	1.57	. . .	1.38	2.00	. . .
5	AE	. . .	1.41	1.94	2.56	. . .

Table 4--Strengths of new stations in a strengthened semi-hexagon

Case	Fixed line	Station				
		A	B	C	D	E
1	AB	. . .	. . .	1.60	2.06	1.28
2	BC	1.79	. . .	. . .	1.79	1.33
3	AC	. . .	1.19	. . .	1.43	1.23
4	BE	1.43	. . .	1.37	1.84	. . .
5	AE	. . .	1.41	1.94	2.41	. . .

before, smaller values represent greater strengths.

Note that the network can be strengthened by including an additional line measured directly from A to D. The numerical values for this strengthened semi-hexagon are computed for the same five locations of the fixed line. The results are given in Table 4.

A comparison of the strengths in Tables 3 and 4 shows that in almost every case the strength gained by measuring the additional line AD is small. Only in case 1, where the fixed line is AB, and then only for the one station D, is the increase in strength significant. Therefore, it is concluded that the measurement of such an additional line is not normally justified.

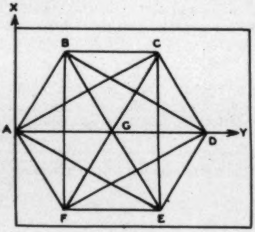

Fig. 4--Hexagon, shape fixed

The hexagonal shoran survey control net (see Fig. 4) consists of seven stations A, B, C, D, E, F, and G with G as center. Sides AB, BC, CD, DE, EF, FA, AG, BG, CG, DG, EG, and FG are all equal. The lines AC, AE, CE, BF, BD, and DF are also equal in length but longer than lines of the first group.

The error equations for all the lines in the network can be established in the same manner as for the quadrilateral and the semi-hexagon. Four cases were investigated for the various positions of the fixed line in the network: (a) side, (b) diagonal, (c) radius with diameter not measured, and (d) side with diameter measured. The resulting strengths at the new stations for the four cases are given in Table 5.

Table 5--Strengths of new stations for a hexagon

Case	Fixed line	Station					
		B	C	D	E	F	G
1	AB	. . .	1.52	1.91	1.91	1.52	1.19
2	AC	1.06	. . .	1.26	1.24	1.26	1.01
3	AG	1.24	1.54	1.72	1.54	1.24	. . .
4	AB[a]	. . .	1.33	1.59	1.59	1.33	1.07

[a] With diameter measured.

The square net shown in Figure 5 was tested in four ways, holding fixed, in turn, AB, AC, AI, and BI. The results are given in Table 6.

Conclusion--The following conclusions are drawn.

(1) For simple triangles, the optimum shape, considering both the strength and the rate of expansion of the figure, will fall in the range for which angle A is between 45° and 75° and the ratio c/b is between 1 and 1.5.

(2) For a quadrilateral, the strongest shape is the square, for which both new stations have the same strength, with their combined strength greater than that of any other quadrilateral. As the shape deviates from that of a square, one of the new stations may gain strength slightly but the other new station rapidly weakens.

(3) For the cases investigated, the maximum mean-position error seldom exceeded three times the mean-square error of the measured length of unit weight. An exception occurs in the simple triangle; only then does the mean-position error become large when undesirable shapes are employed.

Table 6--Strength at different stations for a square net

Case	Fixed line	Station								
		A	B	C	D	E	F	G	H	I
1	AB	. . .	. . .	1.57	2.80	2.68	3.22	2.38	2.16	1.52
2	AC	. . .	1.27	. . .	1.81	1.80	2.04	1.81	1.81	1.14
3	AI	. . .	1.51	1.38	2.07	1.65	2.07	1.38	1.51	. . .
4	BI	1.20	. . .	1.20	1.89	1.58	2.16	1.58	1.89	. . .

The position error for a triangle is large because the new station is located by the intersection of only two lines. Strength is always increased when a new station is located by the intersection of more than two lines.

(4) Assuming a constant mean-square error of unit weight for the quadrilateral, semi-hexagon, and hexagon, the mean-position error for a similarly situated station will be smallest for the hexagon and largest for the quadrilateral. Therefore, the hexagon gives better strength than either of the other two figures, and the quadrilateral is the weakest.

(5) Square nets are also satisfactory for shoran control. As shown in Table 6, the mean position error for all the new stations will not exceed 2.1 times the mean-square error of unit weight except in the one case where an outside line (AB, Fig. 5) is used as a base for extension of the network. In this case the mean position error is at worst 3.22 times the mean-square error of the unit weight.

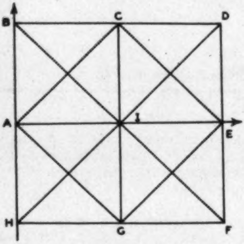

Fig. 5--Square, shape fixed

(6) Although this investigation is confined to figures of a regular shape, in practice, the choice of figures will be influenced by the topographical conditions encountered. Shoran, however, is far less subject to these restrictions than is conventional triangulation, so that figures closely resembling those considered here can be chosen.

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THE PHASED-SUPERPOSED-EPOCH METHOD OF ANALYSIS, AND AN APPLICATION TO GEOMAGNETIC ACTIVITY

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Abstract--This paper describes the phased-superposed-epoch method in which data are grouped according to their phases for analytical treatment. The phases are those of increase, decrease, or no change in geomagnetic activity, and are determined by the characteristics of pairs of days, both individually and relative to each other, on the basis of previously chosen criteria. This method is otherwise similar in some respects to the Chree superposed-epoch method, in which the characteristics of only one day are considered in the grouping of data (selection of reference days). In a limited but demonstrative investigation, the daily magnetic C figures for 1932-1946 were classified according to their level of activity as disturbed D, intermediate I, and quiet Q. The groups of data thus referenced by the three Chree categories and by the nine phases were analyzed on punch-card machines. Some of the results obtained by the phased method for the entire 15-year period, considered in terms of the averaged C values, were as follows: (1) When magnetic activity remains at a generally disturbed, an intermediate, or a quiet level for at least two days, the second day tends to be slightly more quiet than the first. (2) The tendency for the magnetic activity of a sequence of two days to repeat itself after 26 to 28 days is strongest when the two days are at the same level of activity. (3) The phases that recur most strongly 26 to 28 days after their initial incidence are II, QQ, DD, and QD. (4) The phased method makes evident some trends in activity that are smoothed away or reduced in the use of the Chree method.

Introduction--In analyzing data, it is often desirable or necessary to group data so that at least one characteristic is common to all the data in each group. This characteristic (such as chronological location, amplitude, or period) may not always be as monomorphic as is desired or believed, however. Such an unintentionally inclusive grouping can obscure phenomena or information that might have been developed from a different subdivision of the data. This paper describes the phased-superposed-epoch method, a method that defines the characteristic of a day in terms of the phase in which it is included. The phase is determined by the individual and relative magnitudes of two or more values. In the analysis of geomagnetic data the use of phases provides for a greater selectivity in the choice of characteristics than is generally employed in the frequently-used Chree method.

A 27-day recurrence tendency for geomagnetic activity was noticed and studied by Brown, Maunder, and others a number of years before Chree's study added some statistical authenticity to its existence [CHREE, 1913]. The tendency for magnetic disturbance to recur, after an interval of about 27 days from the initial incidence of a disturbance, is commonly related to the rotational period of the Sun. If any one active solar area is sufficiently long-lived it appears opposite the Earth once every 27 or so days in the normal course of the Sun's rotation about its axis.

Chree's study, which showed the 27-day tendency rather clearly, had the desirable feature of using data which were not obtained from direct observation of the Sun. The general relationship of solar and terrestrial activity is deduced in part from the equivalence of the 27-day quasi-periodicities of magnetic activity and of sunspot central meridian passages (CMP) as well as from individual observations of cause and effect, such as solar flares and magnetic crochets. However, neither the specific solar origin of geomagnetically effective solar influences nor the medium by which they are propagated is as yet definitely identified in many cases.

In an effort to learn more about the activity exhibiting a tendency to recur, the writer began the development of this phased method several years ago. A description of it and the superposed-epoch method, and some of the results obtained, follow. Since beginning the study the writer has learned of parallel methods and investigations by BARTELS [1946, p. 232, and 1948], THELLIER and THELLIER [1948], and WULF and NICHOLSON [1948].

The superposed-epoch method--The simplest superposed-epoch method is one such as is used to demonstrate an average daily, annual, or other variation, where, for example, values for each calendar month are grouped together for different years and averaged. The plot of the resulting

Table 1--Example of daily magnetic C figures (× 10) and selections

Dates	C figures									
1943										
Jan. 1-10	$\underline{5}$	2	$\underline{5}\nearrow$	[14]	$\underline{9}$	$\underline{4}$	1	$\underline{4}$	2	3
11-20	2	3	1	0	1	$\underline{5}\nearrow$	[13]	$\underline{6}$	3	[16]
21-30	[13]	[13]	$\underline{5}$	3	1	$\underline{8}$	$\underline{5}$	$\underline{6}$	2	3
31	2									
Feb. 1-9		3	2	$\underline{5}$	$\underline{7}$	$\underline{7}$	$\underline{6}$	3	$\underline{4}$	3
10-19	2	$\underline{4}$	3	$\underline{8}$	2	2	$\underline{4}\nearrow$	[16]	$\underline{5}$	4
20-28	3	2	2	$\underline{5}$	$\underline{5}$	$\underline{11}\nearrow$	[13]	$\underline{6}$	2	
Mar. 1										4
2-11	$\underline{10}$	$\underline{6}\nearrow$	[12]	$\underline{9}$	$\underline{4}$	$\underline{4}$	$\underline{4}$	3	2	$\underline{10}$

[C] = D day ($C \geq 12$).
$\underline{C}$ = I day ($4 \leq C \leq 11$).
C = Q day ($C \leq 3$).
[C] = Chree-method selection.
$\underline{C}\nearrow$[C] = phased-method selection for I ↗ D phase.

Table 2--Example of tabulation of C figures for Chree analysis (D days)

r dates	Day										
	r-2	r-1	r	r+1	r+2	r+3	r+4	r+5	r+6	r+7	r+8
1943											
Jan. 4	2	$\underline{5}\nearrow$	[14]	$\underline{9}$	$\underline{4}$	1	$\underline{4}$	2	3	2	3
Jan. 17	1	$\underline{5}\nearrow$	[13]	$\underline{6}$	3	[16]	[13]	[13]	$\underline{5}$	3	1
Jan. 20	$\underline{6}$	3	[16]	[13]	[13]	$\underline{5}$	3	1	$\underline{8}$	$\underline{5}$	$\underline{6}$
Jan. 21	3	[16]	[13]	[13]	$\underline{5}$	3	1	$\underline{8}$	$\underline{5}$	$\underline{6}$	2
Jan. 22	[16]	[13]	[13]	$\underline{5}$	3	1	$\underline{8}$	$\underline{5}$	$\underline{6}$	2	3
Feb. 17	2	$\underline{4}\nearrow$	[16]	$\underline{5}$	$\underline{4}$	3	2	2	$\underline{5}$	$\underline{5}$	$\underline{11}$
Feb. 26	$\underline{5}$	$\underline{11}\nearrow$	[13]	$\underline{6}$	2	$\underline{4}$	$\underline{10}$	$\underline{6}\nearrow$	[12]	$\underline{9}$	$\underline{4}$
Mar. 4	$\underline{10}$	$\underline{6}\nearrow$	[12]	$\underline{9}$	$\underline{4}$	$\underline{4}$	$\underline{4}$	3	2	$\underline{10}$	$\underline{11}$
Mean	5.6	7.9	13.7	8.2	4.8	4.6	5.6	5.0	5.7	5.3	5.1

averages for each of the month-groups would then illustrate the average annual variation of the activity for those years, particularly if the annual trends are relatively consistent. In essence, the method is used to demonstrate an average cyclic variation of a quantity at a given periodicity.

The Chree superposed-epoch method is used to determine the cycle of time identified with a quantity that varies with time, generally in a quasi-periodic manner. In the Chree method (using daily units of time), stated daily values, levels of activity, or other characteristics as shown in Table 1 govern the individual selection of days to be employed as reference days. Each reference-day value together with the values for the desired number of preceding and following days is entered, using normal chronological sequence, into a row of a matrix or tabulation. One column of the matrix will, by design, contain the reference day of each row (see Table 2).

In this tabulation the number of columns will depend upon the length of the cycle to be studied, and the number of rows will be equal to the number of reference days selected. Each of the columns will, by this manner of tabulation, contain values having a given time separation from individual

Table 3--Example of tabulation for phase analysis (I ↗ D phase)

r dates	Day										
	r-2	r-1	r	r+1	r+2	r+3	r+4	r+5	r+6	r+7	r+8
1943											
Jan. 3	$\underline{5}$	2	$\underline{5}$ ↗	[14]	$\underline{9}$	$\underline{4}$	1	$\underline{4}$	2	3	2
Jan. 16	0	1	$\underline{5}$ ↗	[13]	$\underline{6}$	3	[16]	[13]	[13]	$\underline{5}$	3
Feb. 16	2	2	$\underline{4}$ ↗	[16]	$\underline{5}$	$\underline{4}$	3	2	2	$\underline{5}$	$\underline{5}$
Feb. 25	$\underline{5}$	$\underline{5}$	$\underline{11}$ ↗	[13]	$\underline{6}$	2	$\underline{4}$	$\underline{10}$	$\underline{6}$ ↗	[12]	$\underline{9}$
Mar. 3	$\underline{4}$	$\underline{10}$	$\underline{6}$ ↗	[12]	$\underline{9}$	$\underline{4}$	$\underline{4}$	$\underline{4}$	3	2	$\underline{10}$
Mean	3.2	4.0	6.2	13.6	7.0	3.4	5.6	6.6	5.2	5.4	5.8

reference days. The column averages can usually be considered as representative of days having the specified time separation from that type of reference day. Further descriptions and similar uses of the method can be found in CHREE [1913, p. 97], CHAPMAN and BARTELS [1940, p. 396], and in a related study [CHERNOSKY, 1951, p. 861].

The phased-superposed-epoch method--The phased-superposed-epoch method is designed (as is the Chree method) to determine, among other things, the average cycle of time or quasi-periodicity for a variation inherent in a quantity that is variable with time. In the Chree method a reference day is selected on the basis of its activity alone, or else its activity relative to all days of the month. In the phased-superposed-epoch method the reference day is selected on the basis of its activity as well as of the activity on a following (or preceding) day. An example of a phase selection and tabulation is shown in Tables 2 and 3. Other selections of reference days can be made simply on the basis of the amount and direction of change between two days, with or without dependence on the activity of either of the two days. The tabulation is essentially the same as that for the Chree method.

For an example of a phased-method analysis, the magnetic C values are first classified into three activity categories, for example, the D category containing C figures of 1.2 through 2.0; the Q category for the values 0.0 through 0.3; and the I category for the remaining C values of 0.4 through 1.1, the scheme used in this paper (shown in part in Table 2). One series of reference days could be comprised of those days with C values of 1.2 - 2.0 which were preceded by C values of 0.4 - 1.1 days. These are designated the ID phase (Table 3). Another series of reference days could be the 0.0 - 0.3 days which were followed by the 1.2 - 2.0 days, the QD phase, and so on. Thus, with three categories of magnetic activity, nine different groups of reference days or phases of magnetic activity can be formed, instead of just three as with the application of the Chree method. With the use of the nine phases, large, moderate, and little or no increase or decrease in activity are the changes considered. Other categories can be selected, of course.

The data and their arrangement--The principal data used in this investigation were the 5479 daily international C figures or measures of magnetic activity for the 15 years 1932-1946 (plus January 1, 1947). Each of more than 30 cooperating observatories located around the world evaluates its Greenwich-day record by assigning one of the three digits (0) quiet, (1) moderately disturbed or disturbed, and (2) very disturbed, according to a numerical scale proposed by Schmidt in 1905. These C figures have been collected and averaged by van Dijk, Johnston, Scott, Balsam, and others, who have thus obtained decimal values from 0.0 to 2.0 for each Greenwich day. These daily values are available in CHAPMAN and BARTELS [1940, Table J]; VESTINE and Others [1947, Table 1-U], IATME Bulletins of 1948, and elsewhere currently. Three activity categories denoted by D, I, and Q or, by numerical notation for later reference, 12, 4, and 0 respectively, were formed for this study, as prescribed in the preceding paragraph.

The nine phases for the two-day sequences will be referred to as the 12-12 or DD, the 4-12 or ID, the 0-4 or QI, etc., phases. The first day of the pair of days is designated as the reference or r day. After tabulating in accord with the method used, averages were obtained for each column of days from (r - 39) to (r + 40) days of each of the nine phase groups and of each of the three Chree groups.

Table 4--Distribution of days by C figure category and phase

Item	Category								
	D (1.2 - 2.0) 974 days = 17.8 pct			I (0.4 - 1.1) 2649 days = 48.3 pct			Q (0.0 - 0.3) 1856 days = 33.9 pct		
	DD	DI	DQ	ID	II	IQ	QD	QI	QQ
Number of days	455	474	45	400	1530	719	119	644	1093
Per cent (actual)	8.3	8.7	0.8	7.3	27.9	13.1	2.2	11.8	19.9
Per cent (expected)[a]	3.2	8.6	6.1	8.6	23.3	16.4	6.1	16.4	11.5
Ratio, actual/expected	2.60	1.01	0.13	0.85	1.20	0.80	0.36	0.72	1.7
Difference, actual - expected	4.1	0.1	-5.3	-1.3	4.6	-3.3	-3.9	-4.6	8.4
Weight, ratio × difference	13.2	0.1	-0.7	-0.6	5.5	-2.6	-1.4	-3.3	14.5

[a] Computed on basis of a random sequential association of C figures.

Results--Most of the results are shown in graphical or tabular form. The quantitative breakdown of the 5479 daily values into three categories and into the corresponding nine phases is shown in Table 4 and Figure 1. Plots of the averages computed from tabulations, in which reference days were selected and groupings of the 15 years of data were made according to the phase as well as by the Chree method, are shown in Figures 2, 3, and 4. (The three phase curves of each figure, when combined, give the Chree curve accompanying them.)

A comparison of the ratios of the actual to the expected frequencies gives evidence of the high serial correlation (positive conservation or auto-correlation of successive values) which is characteristic of C figures; see **CHAPMAN** and **BARTELS** [1940, p. 582]. To obtain an idea of the serial correlation of C figures, as grouped in these categories, the expected frequencies of occurrence of each phase are computed on the basis of a random sequential association of categories (that is, for the DD phase 17.8 pct × 17.8 pct = 3.2 pct expected). The II, QQ, and DD (or same category) sequences constitute 56.1 pct of the total days or 1.48 times the expected quantity. The small-change sequences, IQ, QI, DI, and ID, are found about 0.82 times expectancy, and the large change sequences, QD and DQ, occur three per cent of the time or 0.25 times the random expectancy. As a group the increasing activity phases, QI, ID, and QD, appear with a frequency 0.68 times expectancy, and the grouped decreasing phases , IQ, DI, and DQ, constitute 22.6 pct of the values or 0.75 times the random expectancy. Use of smaller categories would undoubtedly have resulted in a lower serial correlation.

Certain features of the average trends in activity shown by the days in or adjoining the phases can be remarked upon. For the no-change phases involving like categories, the second day of the

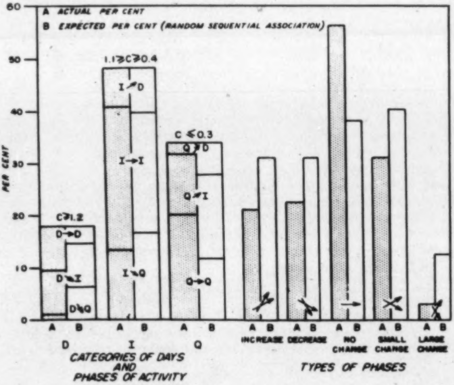

Fig. 1--Classification of magnetic activity (1932-1946)

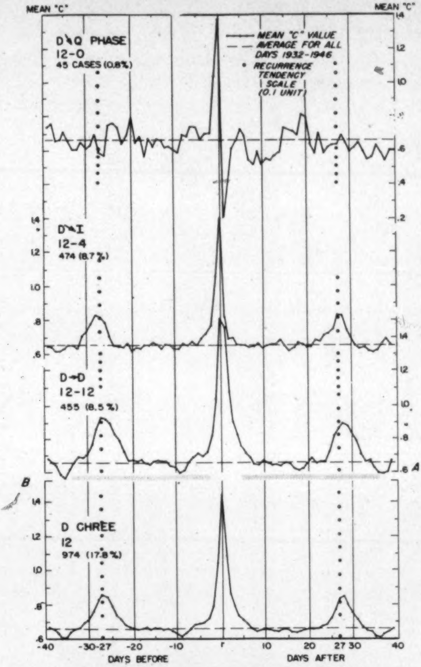

Fig. 2-- The morphology of magnetic activity associated with different selections of disturbed-category reference days; (A) phased-method selection; (B) Chree-method selection (or combined three phases)

selected sequence is more quiet, on the average, than is the first day, even in the quiet-day sequence. In the two or three days adjoining the phases, including the quiet category, the disturbance rises faster than it subsides, exclusive of course of the change between the two selected or reference days. Such an observation of more rapid increase is in accord with CHREE's [1913, p. 109] findings. This difference in rate of rise and fall of activity is further shown by the fewer number of days participating in the rise phases than in the fall phases, and consequently larger increments of rise than of fall in activity. This is the case where the rise and the fall of activity approximately equal each other over the period of time considered (as the C figures do).

In the increasing- or decreasing-activity phases beginning or ending in the intermediate category, the selected intermediate-category-day averages indicate an activity level that is intermediate in the three-day trend beginning or terminating in the other selected day of the phase.

The tendency for much or little activity to recur (recurrence tendency or RT) in like form, 26 to 28 days after its initial incidence, is computed here from the ratio of the average of the preceding and subsequent pulses to the selected-day pulse. The pulses are measured in terms of the maximum departures from the average value of all days (1932-1946) to obtain the pulse ratio RT. The RT is

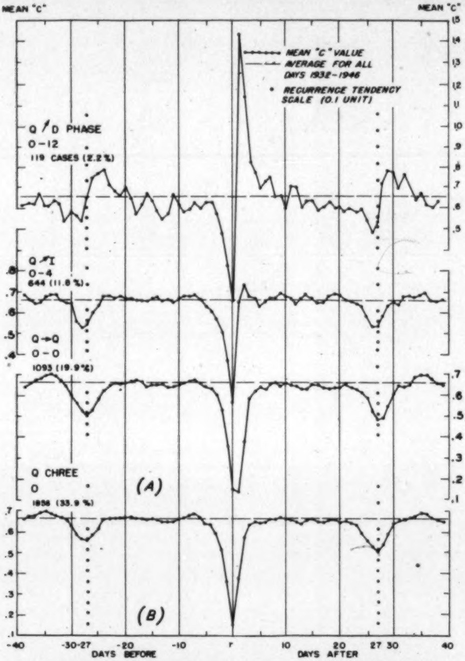

Fig. 3--The morphology of magnetic activity associated with different selections of quiet-category reference days; (A) phased-method selection; (B) Chree-method selection (or combined three phases)

strongest for the like-category phases (Table 5). When the secondary pulses of the phase groups are referred to the category average, considering this average as the maximum expected deviation, the RT is slightly stronger than when referred to the phase-group, selected-day average. The pulse associated with the DQ phase or "sudden termination" (ST) is the only pulse not exhibiting any 26- to 28-day RT, showing, if anything, a 20-day recurrence interval for the 15-year grouping.

The strongest recurrence is not shown by the disturbed- or quiet-day pulses, but by the amplitude of a unidirectional change occurring over several days and associated with the II phase. In this phase the four-day decrease in activity of the r to (r + 4) days recurs 27 days away at about 70 pct of its amplitude. This RT is about twice that for the D or Q pulses. Although the amplitude is small, this phase represents a very large number of cases. The RT for the other phases can be given a qualitative estimate only; they recur, strongest to weakest, in the following order: DD, QQ, QD, ID, DI, IQ, QI, and DQ.

It is found that the maximum of the reference pulse does not always appear midway between the corresponding preceding and subsequent secondary pulses. The mid-point of the secondary pulses is at (r + 1/2) day for the DD and possibly for the D groups; at (r - 1/2) day for the DI group, and at (r - 1) for QI instead of at r day; at (r + 1/2) for ID, and at (r + 2) for IQ instead of at (r + 1); for

Table 5--The 27-day recurrence tendency (RT) as determined from Chree and phased-method groups[a]

Item	Category of day used in computing RT								
	D				I	Q			
	DD	DI	DQ	ID	II	IQ	QD	QI	QQ
Chree method (relative to primary pulse)	← 0.25 →				0.60[b]	← 0.28 →			
Phased method (relative to primary pulse)	0.30[c]	0.23	--	0.22	0.73[b]	0.26	0.27	0.26	0.30[c]
Phased method (relative to category average)	0.31[c]	0.22	--	0.22	--	0.27	0.27	0.26	0.31[c]

[a] Means from preceding and subsequent secondary pulses.
[b] RT is determined for the 4-day decrease of activity of r to r + 4 days; see text.
[c] RT is determined for the pairs of like days (DD and QQ).

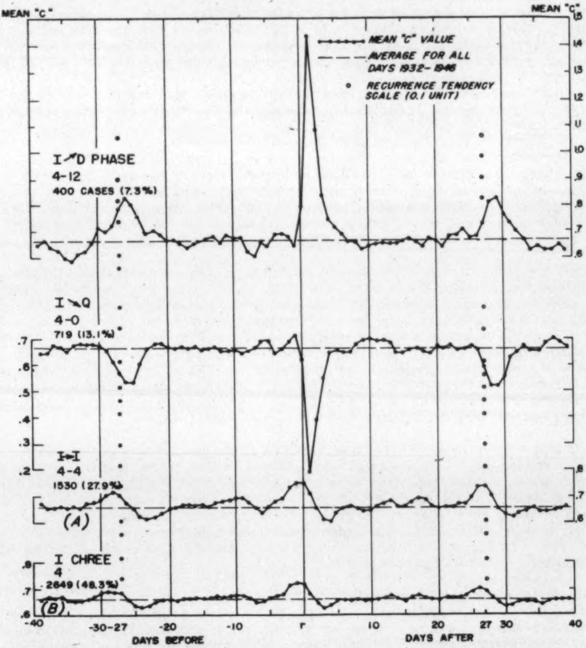

Fig. 4--The morphology of magnetic activity associated with different selections of intermediate-category reference days; (A) phased-method selection; (B) Chree-method selection (or combined three phases) the QD phase the D days centered at about (r + 2 1/2) rather than at (r + 1) as expected, and the Q days at about (r - 1) instead of r day.

In addition, certain results that were noted will have to be given further attention to be properly evaluated. Among these are:

(1) The roughly exponential decrease in activity for about 25 days following the QD phase. This decrease, which is usually expected for a few days after a disturbance, appears in each of the two rotations covered. About two per cent of all days (four per cent if both of the reference pair of days are counted) are included in this phase. On the basis of an exponential decrease in activity one might speculate on a long decay period for upper atmospheric ionization or ionospheric currents if magnetic disturbance can be considered a function of such phenomena.

(2) The slight tendency for activity to increase generally over about a 20-day period following the decrease in activity of the II sequence during r to (r + 4). This slight increase, existing in a large amount of data, repeats itself each solar rotation for both the II phase and the I Chree curve.

(3) The possible existence of a 4- to 6-day Deslandres interval that occurs between about (r + 10) and (r + 20) days. This quasi-periodicity appears most strongly in the phases including the I category and least so in the phases including the D category. Chree had not been able to find this interval that Deslandres felt did exist.

(4) The occurrence of a deviation in the opposite sense from that of the selected-day pulse, an anti-recurrence, or negative pulse some 34 to 36 days before and after the selected-day pulse. These anti-recurrences appear most strongly with the DD, D, QQ, and Q groups, but may have a statistical rather than a real origin. They are in evidence at the ends (the 35th day) of the sequences of days of Chree's studies.

(5) A possible tendency for disturbances to recur about 20 days before and after the DQ selected days. A DQ phase, or sudden termination is rather unusual under the concepts of magnetic storms and deserves attention.

Discussion--For more than half a century, many investigators have used diverse analytical methods in examining magnetic data, bequeathing to the student of geomagnetic activity an apparently poor prospect for extracting still more information from the data. Nevertheless, it appears that the superposed-epoch method, wherein phases or the characteristics of two or more days are employed in selecting reference days, does provide new information on magnetic data, some as expected, some not, but at least with a degree of statistical substantiation.

Not all of the potentialities of this phased method have been demonstrated in this paper, but other results will be considered in a later paper. The other researches, previously mentioned, in which the properties of more than one day were considered in making a single selection, have been concerned not with all possible phases for the groupings employed, but rather with more-or-less individual or specific characterizations. BARTELS [1932, p. 232] performed two statistical experiments with pairs of reference days selected at times of sudden rises or falls of sunspot number, and looked for recurrences of the same. In other work BARTELS [1948] considered the activity of each day of groups from three to eight days in selecting reference days. Bartels' selections comprise certain specific cases of the more general DD, QQ, QD, and DQ phases covered in this phased-method study, and also employed C figures for the years 1884-1943.

The DD type selections were based upon separate groupings for each of the sequences where non D days preceded and followed single D days, double D (DD), triple D (DDD), and up to six consecutive D days. Similar groupings were made for the six sequences where non Q days preceded and followed Q days. For the equivalent QD group selections four Q days preceded a D day which was followed by non Q days. For the DQ group a D day had to be preceded by non Q days and followed by four Q days. The recurrence tendency was found to be stronger for the longer sequences of selected days, a finding with which this study is in agreement. Also fewer of the DQ type than the QD type sequences were found in both studies.

This investigation was mentioned briefly to Sydney Chapman who called the author's attention to possibly similar research conducted by THELLIER and THELLIER [1948]. The criterion for the selection of reference days was not stated, but it appears that only the largest disturbances were considered. The disturbances were selected from magnetograms and the corresponding C values were studied. The 210 cases of sudden commencements showed no 27-day recurrences, but the 328 progressive-commencement cases did so, thus confirming, in their opinion, Greaves' and Newton's results regarding intense storms. These findings would be in opposition to those obtained with the phased method if the sudden and progressive commencements were equivalent to the QD and ID phases respectively. However, further information is needed to compare the results adequately.

WULF and NICHOLSON [1948] investigated some cases of abrupt onsets in magnetic activity associated with appearances of active solar regions. These abrupt onsets, very similar to the QD phase, were found to occur in each of as many as 12 rotations of the Sun.

Some aspects of the phased method and its results can be discussed in more detail. The major features of the phased method are best exhibited in Figures 2, 3, and 4. Each of the figures shows data for three phased analyses; these data when combined give the familiar Chree graph shown in the fourth curve. Any quasi-periodicities, trends, or relevant detail appearing only in the phased curves can be considered to be information obscured by the more-inclusive grouping of the Chree method of reference-day selection.

It is of interest in some statistical considerations that consecutive days, or overlapping pairs of days, can be selected as reference days for the Chree groups and for the like-category phase groups. The two groups differ primarily in that one day less of an unbroken series of days in the same category is included in the phase group than in the Chree group; furthermore, isolated or single days of the selected category would appear, but only in the Chree group. For example, in the like-category phase group, a four-day sequence of disturbed days would be represented by three reference days (three overlapping pairs) while one-day disturbances would not appear at all. For the phases involving unlike categories, consecutive days cannot be selected for reference days. Only consecutive pairs of days can contribute a reference day (every other day) to the group, but the high conservation of C minimizes this possibility. See also the discussion by BARTELS [1948, section 3.2.3.3.2].

The phased method takes into account (within wide limits in this study) the degree of correlation between the selected days at least. It may be considered that the phases involving unlike categories have reference days selected at breaks in the high conservation of C. The like phases would therefore have reference days at points of highest conservation. The correlation of the two selected days alone appears to have a positive general relationship to the strength of the 26-28 day recurrence tendency. The effect of the correlation factor may be best evaluated by selecting reference days on the basis of the difference between them, as is to be done in a succeeding investigation. It is to be noted that the small-change phases involving the D and I or I and Q categories will include some highly conservative sequences with changes as little as 0.1 of a unit in C (0.3 - 0.4, 1.1 - 1.2, 0.4 - 0.3, and 1.2 - 1.1).

In the like-category phases, in which the strongest recurrence tendency is noted, the features or salients of the related Chree curve are generally emphasized in the phase curve. Since the like-category phases include the longer disturbed or longer quiet periods the correspondingly greater opportunity for superposed sequences of two or more days of like activity to coincide, for at least one day at 26-28 day intervals, may contribute to a stronger RT for these phases.

As is evidenced by the usual RT of much less than unity, all magnetic activity does not necessarily recur, in similar sequence or type, after an interval corresponding to the solar rotational period, because of probable change in the solar phenomenon that is responsible. The displacement of the reference (r day) pulse from the mid-point in time between the two secondary pulses, where it occurs, is attributed to the unequal contributions to the selected-day average on the part of the less numerous, more recurrent, and the more numerous, less recurrent types of activity. For example, in the ID phase the averages indicate an IDI sequence with a large value of I after the selected D day. This IDI sequence, in all probability, would be composed of IDI, IDD, and IDQ sequences, in order of descending number. This composition is indicated from the relative proportions of DI, DD, and DQ phases as well as the average values for the three days including the reference pulse. As the DD sequence is found to have the strongest RT of the D category, it is very likely that the IDD sequence is identified with the activity that recurs after 26 to 28 days. Thus, since the DD group has a peak of recurrence at the (r + 28) day and a primary peak at r day, the IDD primary peak at (r + 1) day and secondary peak at (r + 29) are in accord.

An examination of the graphs suggests that the recurrences are due mainly to DD or QQ groups, or both. Thus, the three-day recurrent sequence is IDD for the ID phase, DDI for DI, QQI for QI, IQQ for IQ, and QQDD for QD, and perhaps DDQQ for DQ if any.

BARTELS [1932, p. 51] noted and estimated, from his 27-day diagram of magnetic activity, that C values of 0.8 to 1.6 tended to recur for many solar rotations. Inasmuch as the strongly-recurrent I category (C of 0.4 - 1.1) coincides in part with the Bartels estimate, some confirmation of his finding is afforded.

Conclusion--The phased method appears to be a simple and effective analytical method for obtaining some new information from geomagnetic data. This additional information should contribute to an increased understanding of geomagnetic activity and of solar-terrestrial relationships. It is the purpose of the phased method to provide for a homogeneous selection of reference days, but in this investigation the inclusion of some heterogeneities, due to variations during the solar cycle, will have been disregarded. However inclusive these groupings may have been as a result, the following features or homogeneities have been developed from the averages obtained in the different groups:

(1) Where one day is followed by another day of the same activity category (disturbed, intermediate, or quiet) the second day is more quiet than the first.

(2) The recurrence tendency appears to vary roughly in some proportion to the serial correlation of the two selected or reference days.

(3) A very strong repetition of a pattern of activity, which may be termed a recurrence tendency, is exhibited by a sequence of four days of decreasing activity of the II phase.

(4) Salients existing in a Chree curve appear with greater emphasis in the corresponding no-change phase curve, thus indicating a strong association of the salients with the activity of the reference day(s).

(5) The phased method exhibits trends or detail that can be averaged out much more or lost entirely in the Chree method; the use of the phased method is therefore recommended, particularly for the analysis of large quantities of data.

Acknowledgments--The writer first conceived an idea for a phased method of analysis several years ago while at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. Experimentation with the method has been conducted at intervals in the intervening time. The writer is indebted to S. Chapman for calling attention to the paper by Thellier and Thellier, and to E. H. Vestine for relaying information from J. Bartels concerning his work abstracted in the FIAT review. Thanks are due to the Mechanized Analysis Group, E. A. Hogge, E. Maple, and L. R. Alldredge for facilitating some aspects of the work. Appreciation must be expressed also for the work of a great number of people who have contributed to the existence and availability of the C figures, without which investigations such as this would not be possible.

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ON THE ELECTRICAL CONDUCTIVITY OF THE LOWER STRATOSPHERE

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Abstract--The reality of the decrease of conductivity with height observed at the top of the Explorer II flight is supported by some measurements made earlier by Idrac. The cause of this decrease is discussed and an hypothesis of convective updraft of Aitken nuclei from troposphere to stratosphere is examined. The hypothesis appears incapable of accounting for a steady-state worldwide population of stratospheric nuclei sufficient to satisfy existing observations. It is urged that Idrac's measurements be repeated on a more extensive basis using more modern sounding techniques.

Introduction--One of the many results of the 1935 stratosphere balloon flight of the Explorer II was the observation of a surprising decrease of atmospheric electrical conductivity with height through the top few kilometers (19-22 km) of that flight. GISH and SHERMAN [1936] have discussed this feature of the sounding, and GISH [1939] has made some suggestions as to its possible origin; but no further attention seems to have been given this matter until HOLZER and SAXON [1952] recently examined, on theoretical grounds, the current distribution that may be expected to exist above and around an active thunderstorm. They approached this problem in an effort to check the significance of the important thunderstorm electrical measurements made by GISH and WAIT [1950].

Holzer and Saxon employed the assumption that atmospheric conductivity increases exponentially and hence monotonically with increasing height through the troposphere and stratosphere all of the way up to some conducting layer in the lower ionosphere. In making this assumption, these authors did not overlook the Gish-Sherman observations of a conductivity minimum, but they chose to omit this feature from their analysis on the basis that it is not known whether this represents a commonly occurring condition of the lower stratosphere or whether it was an anomaly peculiar to the Explorer II sounding. Holzer and Saxon point out that a shallow layer of low conductivity would not alter their principal conclusions concerning the ionospheric destination of the currents measured by GISH and WAIT [1950], but emphasize that such a layer could have a marked effect on certain other atmospheric electrical phenomena, notably the vertical-field fluctuations observable at the Earth's surface at distances of the order of many tens of kilometers from active thunderstorms.

Earlier evidence for a stratospheric conductivity decrease--The discussion by Holzer and Saxon has pointed up the uncertainty as to whether a stratum of low conductivity is a common, or indeed even a real, feature of the stratosphere and has prompted the present writer to call attention to an earlier study of the electrical state of the lower stratosphere in which there was found indirect evidence for a decrease of conductivity similar to that found in the Explorer II sounding. IDRAC [1926] made a number of balloon soundings of the vertical electric field intensity over Trappes, France, during a single day in June, 1926. Three of his releases led to soundings extending above 13 km and in these three Idrac found that the field intensity, after decreasing in the characteristic manner through the troposphere, started increasing above the tropopause. The average field strength at eight kilometers for all of his flights for that day was only 2.3 v/m, while in the region above 13 km it reached values as high as 40 v/m. Assuming a uniform vertical current density for all heights reached by Idrac's balloons, one finds that these intensity values imply a conductivity decrease by a factor of almost 20 in going from eight kilometers up to this level of maximum local field strength above 13 km. Fortunately, one of Idrac's flights extended to 20 km and revealed that the field intensity decreased again above 16 km, falling to 1.2 v/m at 19 km, thus showing that the conductivity did not remain low that day throughout the vertical extent of the stratosphere over France.

These observations by Idrac were not discussed by Gish and Sherman, with the result that there has probably been less significance attached to the Explorer II results in the 19-22 km region than might otherwise have been the case. Idrac's findings seem particularly valuable in that they refer to a region remote from that in which the Explorer II flight was made and to a time several years earlier, thus casting doubt on any supposition that the sort of low-conductivity stratum found by Gish and Sherman was an anomaly peculiar to that sounding. Furthermore, Idrac's measurements suggest that there may be only a rather thin layer of low conductivity in the stratosphere, while the Explorer II observations left this important point indeterminate. This latter contribution of Idrac's work strengthens the position taken by HOLZER and SAXON [1952] with respect to the slight importance of any regions of low conductivity in altering the upward flow of positive current from thunderstorm to ionosphere, while the former contribution (indication of worldwide extent of the low-conductivity layer) points to the need for further study of the suggestion made by Holzer and Saxon that such a layer may strongly influence surface field-strength fluctuations far from active thunderstorms and squall lines.

Possible causes of the conductivity minimum--Despite the lack of agreement between Idrac's observations and those by Gish and Sherman as to the altitude of the base of the region of low conductivity , their agreement as to the presence of such a region in the lower stratosphere would seem to justify some attempt to find an explanation for its existence. Atmospheric conductivity is almost entirely controlled by the small-ion density of the air, and this density is in turn controlled jointly by the rate of ion formation (by cosmic-ray-produced ionizations followed by molecular attachment) and by the rate of destruction (by recombination processes and by attachment to Aitken nuclei, forming relatively immobile large ions); hence one must search for some phenomenon capable of locally altering one or both of these rates in the stratum under consideration. There would appear to be no basis for believing that there might be any local decrease of cosmic-ray bombardment here, nor any local anomaly in the molecular attachment rates or in the recombinative processes for small ions, so one is led to seek an explanation for the low conductivity in terms of the effect of some local concentration of nuclei in the lower stratosphere. GISH [1939], in first discussing this type of explanation, suggested the possible role of nitrogen pentoxide which has been detected spectroscopically in the region from 16 to 40 km. GISH [1951] has also noted that ozone was found to be unusually abundant near the top of the Explorer II sounding, but he has not indicated how either of these substances might ever appear in the form of particles large enough to serve as large-ion nuclei.

Convective transport of nuclei--The writer has been led to consider quite a different hypothesis which seems, at first inspection, qualitatively more probable than those advanced by Gish. This hypothesis would account for the presence of a stratum of Aitken nuclei in the lowest portion of the stratosphere in terms of injection of nucleus-rich air into the base of the stratosphere by thunderstorm updrafts that sweep the air up through the troposphere from the lower levels of higher nuclear density and then expel this air into the stable base of the isothermal region. The nuclei so added from time to time by thunderstorms around the world would not remain forever in the lower stratosphere but would slowly leave this region by virtue of the joint action of fall-out and turbulent diffusion. The critical test of the hypothesis thus becomes that of inquiring whether the processes of addition and removal might reasonably be expected to come to balance with a steady-state nuclei count at the base of the stratosphere sufficient to explain the sort of decreased electrical conductivity found by Idrac and by Gish and Sherman.

Thunderstorm heights--First it may be noted that the heights to which thunderstorms extend are in reasonable agreement with the convective hypothesis, at least for the Idrac observations of a low-conductivity layer with its base near 13 km. The average heights of the tops of thunderstorms observed by radar during the Thunderstorm Project [BYERS and BRAHAM, 1949] was slightly over 11 km, and 40 pct of all observed storms built up to 13 km or above. It is, of course, no mere accident that the base of the stratosphere coincided closely with the maximum altitude reached by thunderstorm updrafts since the stable density distribution above the tropopause precludes appreciable growth into the stratosphere.

The location of the low-conductivity layer in the Explorer II sounding is higher than can be accounted for in terms of average thunderstorms of middle latitudes, and particularly so for the November date on which the flight was made. Examination of the temperature distribution prevailing during the flight [BROMBACHER, 1936] reveals that a double tropopause existed over South Dakota on that day. The lower inversion began at 11.5 km, and the upper at about 18.7 km. This plus the fact that the winds near the top of the flight were southwesterly suggests that the balloon may have been in air that had recently come from lower latitudes of the Pacific area where thunderstorm convection is better able to transport air to heights approaching those at which the Explorer II encountered the decrease of conductivity. However, this necessity of an appeal to a tropical origin of the nuclei over South Dakota must be regarded as a weakness of the thunderstorm hypothesis and if further measurements of stratospheric conductivity should reveal that the average level of the minimum agrees more closely with that found by Gish and Sherman than with that indicated by Idrac's work, one could not even consider the convective explanation here proposed.

Rate of convective transport of nuclei--The first step in a quantitative check of the convective hypothesis consists in estimating the average worldwide rate of thunderstorm transport of nuclei up to the base of the stratosphere. Using data on the average vertical distribution of Aitken nuclei based on 28 balloon flights in the troposphere [LANDSBERG, 1938], and combining these with some recent estimates of the vertical distribution of thunderstorm inflow rates [BRAHAM, 1952], one finds that, during the entire lifetime of an average thunderstorm cell of the middle-latitude type considered by Braham, about 3×10^{20} nuclei may be expected to enter the updraft. Of this total, almost three-fourths of the nuclei are found to enter the cell in the 0-1 km layer. At greater heights, where the mass of air entrained is larger than in the surface layer, the nuclei count has fallen off so much that the weighted average inflow of nuclei is much less than in the 0-1 km interval.

Not all of these 3×10^{20} nuclei are to be regarded as reaching the outflow region at the very top of the storm, however. A certain number will serve as condensation nuclei and will thus be largely removed by the precipitation process, but this number is so small compared to the total number of Aitken nuclei (most of which are too small to be activated for growth) that it may be ignored here. Second, relative motions of nuclei and cloud drops will remove some nuclei by accretion, but this mechanism will also be ignored here on the ground that the collection efficiency for this capture process will be very low in view of the small size of the nuclei. The third process, which cannot be ignored, is that of horizontal outflow of updraft air prior to its reaching the tropopause. Again Braham's data on mass exchange in thunderstorms provides a basis for an estimate. BRAHAM [1952] finds that of the total of 9.0×10^{10} kg of air entering an average storm throughout its duration, only 1.8 by 10^{10} kg flows out at the 200-mb level (about 12 km). Thus, one may regard only 1.8/9.0 of the total of 3×10^{20} nuclei, that is, about 7×10^{19} nuclei, as being expelled from the storm top into the lower layers of the stratosphere. It must be admitted that present ignorance of the details of the kinematics of the outflow pattern at these levels leaves doubt as to whether even this latter number of nuclei may safely be assumed to remain at the outflow level rather than to subside back into the upper troposphere, but this assumption will be made here.

Taking the average lifetime of a thunderstorm cell as about one hour [BYERS and BRAHAM, 1949], and using the estimate by GISH and WAIT [1950] of 3×10^3 storms as the average instantaneous rate of occurrence of thunderstorms over the entire globe, one finds an average rate of stratospheric addition of 6×10^{19} nuclei per second for the whole world. Overlooking the fact that this rate of transport must certainly decrease rapidly with increasing latitude to nearly zero values in both polar regions, one finds that for the entire area of the Earth, 5×10^{18} cm^2, the average rate of thunderstorm injection of nuclei into the base of the stratosphere may be of the order of ten nuclei/cm^2 sec.

Rate of fall-out of nuclei--Having estimated the rate of addition of nuclei, the next step is to estimate the rate of removal in order to compare these two rates as a test of the convective hypothesis. GISH and SHERMAN [1936] have given estimates of the density of nuclei required to account for the low conductivity in the 19-22 km interval of their Explorer II measurements, so in spite of the fact that this interval lies several kilometers above the level to which one may expect thunderstorms to penetrate in middle latitudes, and in spite of the authors' warning that not too much quantitative significance should be attached to their nuclei estimates, these values will be used here as the only available estimate of the nuclear densities in the lower stratosphere. Certain additional deductions can be made from Idrac's data, and note will be taken of these later.

Most Aitken nuclei are less than about 2×10^{-5} cm in diameter [JUNGE, 1951]; therefore, Stokes' law may be applied with reasonable accuracy. Assuming a mean density of 2 gm/cm^3 for the nuclear substances, the particles may be expected to have a maximum fall velocity of only about 10^{-3} cm/sec, that is, less than a meter per day for even the largest. The average instantaneous rate of fall-out per unit horizontal area of the stratosphere is then given by the product of this velocity and the prevailing nuclear density, which we may take as 2×10^3 nuclei/cm^3 [GISH and SHERMAN, 1936]. Thus the downward gravitational flux of nuclei is only about two nuclei/cm^{2}sec. This is almost an order of magnitude less than the estimated rate of addition of nuclei by updrafts, so if fall-out were the sole mechanism capable of removing the nuclei from the stratosphere, one could conclude that the convective hypothesis was confirmed by the above estimates; but in addition, downward turbulent diffusion must be considered.

Turbulent diffusion of nuclei--The rate of vertical turbulent diffusion of nuclei in a layer depends on the eddy diffusion coefficient D, and on the vertical density gradient of the nuclei, dn/dz. LETTAU [1951, Fig. 2] gives 10^5 cm^2/sec for the diffusion coefficient at the 15-km level, and from GISH and SHERMAN [1936, Fig. 7] one finds the density gradient in the layer of low conductivity to be about 10^{-2} nuclei/cm^4. Hence for this combination of data the turbulent flux is

$$D\,dn/dz = (10^5\ \mathrm{cm}^2\ \mathrm{sec}^{-1}) \times (10^{-2}\ \mathrm{cm}^{-4}) = 10^3\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$$

downward. This rate is three orders of magnitude greater than the rate of fall-out, so it appears that one may quite safely neglect fall-out as compared with diffusion. But more pertinent to the present discussion is the fact that the estimated rate of downward diffusion of nuclei is some 100 times greater than the estimated rate of addition of nuclei by thunderstorms (10 nuclei/cm^2sec). One seems forced to conclude that the convective transport hypothesis is quantitatively inadequate for accounting for a uniform, worldwide stratum of high enough nuclear density to fit the Explorer II conductivity measurements.

Discussion--Having found this negative result in the effort to check the convective hypothesis, it is interesting to note that if one seeks points in the computations where some modification might be made, these appear to be almost entirely changes that only strengthen the evidence against the hypothesis.

First, the data on nuclear densities in the troposphere [LANDSBERG, 1938] were obtained from balloon flights made over well settled areas where industrial pollution tends to give counts unrepresentatively high for the world as a whole, so any revisions here would certainly lower the estimated convective transport rate.

Second, the assumption that all of the air diverging from the thunderstorms at the 200-mb level remained, along with its suspended nuclei, at the level of outflow cannot be defended too well. A thunderstorm that builds up to the tropopause probably succeeds in locally pushing up the stable overlying stratospheric air but complete intermixing of the outflow with stratospheric air, as assumed above, is a rather unlikely extreme. If any corrections could be made here, they would undoubtedly lower the effective rate of convective addition of nuclei.

Third, an attempt to incorporate Idrac's findings into the estimate of the downward diffusion of nuclei from the underside of the stratum of low conductivity yields an even higher rate of removal than was found above from the data of Gish and Sherman. Idrac reports a nearly twenty-fold increase of field strength between eight kilometers and about 14 km, which implies a roughly equal factorial decrease of conductivity in this interval. GISH and SHERMAN [1936, Fig. 4], on the other hand, found a conductivity decrease of a factor of only two in the interval from 19 to 22 km. This difference in implied nuclear gradients is thus seen to amount to about a factor of five, making it correspondingly more unlikely that thunderstorm updrafts are steadily counterbalancing downward diffusion of nuclei.

Fourth, one might choose to use the eddy diffusivity value corresponding to the interval in which the conductivity decreased in the Explorer II sounding (19-22 km) rather than to use the value for the 15-km level as was done above in an effort to simulate conditions prevailing just above the tropopause. LETTAU [1951] gives $10^3\mathrm{cm}^2$/sec for D at this level (down a hundred-fold from D at 15 km), so combining this with the previously considered value of the density gradient one obtains an estimated diffusion rate of 10 nuclei/cm^2sec. This is just the estimated transport rate, so this fourth revision is the first one to favor the convective hypothesis. But since this revision requires that one deal with altitudes too great to match observed thunderstorm heights for any but tropical latitudes, it provides no real support for the convective hypothesis anyway. It is, however, interesting to note that LETTAU [1951] has suggested that the very rapid decrease of D with height just above 15 km must tend to produce what he terms a "dust horizon" at this level, and cites some light-scattering observations in support of that contention. This theoretical and observational evidence for some sort of zone of accumulation just above the tropopause does give further support to the view that a layer of high nuclear density and hence low conductivity is the rule rather than the exception in the lower stratosphere, but does not clarify its ultimate origin.

In all, it would seem to have been shown here that the convective hypothesis for transport of nuclei to the stratosphere, though qualitatively quite plausible, is not quantitatively compatible with such observations of the conductivity minimum as exist at present.

Concluding remarks--That Idrac's observations of the vertical variation of the electric field intensity should constitute the only check on the decrease of conductivity with height in the lower stratosphere found in the Explorer II flight, and that even this check should have gone so long unnoticed, seems regrettable. Present-day balloon-sounding techniques should be readily capable of providing data on the behavior of the field up to almost 30 km. Hence the writer recommends that repetitions of Idrac's measurements be carried out at enough different localities and times to determine whether a layer of low conductivity is in fact always present just above the tropopause, and if so to determine at what heights it lies and whether it is uniform or patchy in nature. A series of such soundings might clarify many of the questions raised in the present examination of the convective hypothesis of the origin of such a layer. Such measurements would also shed light on the interesting suggestion [HOLZER and SAXON, 1952] that a layer of minimum conductivity could be responsible for exaggerated surface field fluctuations far from active thunderstorms.

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Editorial Note: We are informed that a later and fuller report of the 1926 work is the following:

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A SIMPLE RECORDING TECHNIQUE FOR DETERMINING RAINDROP SIZE AND TIME OF OCCURRENCE OF RAIN SHOWERS

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(Contribution No. 659 of the Woods Hole Oceanographic Institution)

Abstract--This paper describes an easily constructed instrument for the purpose of obtaining a continuous record of the time of occurrence and duration of shower-type rains and their range of raindrop sizes. A battery-driven motor pulls paper tape, previously treated with the water-soluble dye, methylene blue, past an opening exposed to the rain. The spot diameters left by the rain on the tape may be related to raindrop size by laboratory calibration. During a week's run on the island of Oahu, Hawaii, a total of 119 rains were recorded. Although many of these passed in a minute or so and were only a few minutes apart, less than 40 were recorded by nearby recording rain gages.

Introduction--The drop recorder described in this paper is a simple instrument which records the imprint of raindrops on a moving paper tape. Although it was designed for one specific job, the simplicity of its construction coupled with the interesting data it has obtained may render it useful for other investigations as well. It was initially designed to satisfy the need of obtaining the frequency of occurrence and the predominant drop sizes of rain on the windward and leeward sides of the island of Oahu, Hawaii.

The prime advantages of the recorder are: (1) Compactness and lightweight (3.2 kg). (2) Relatively simple and inexpensive to build. With the exception of the small six-volt motor, all parts should be obtainable in any machine shop. (3) Portability. As the motor is driven by a six-volt dry cell, the drop recorder can be used in locations relatively inaccessible to many instruments. The present model uses two 15-watt, 115-volt lamps for drying the exposed tape. To make it completely independent of a 115-volt power supply, a self-enclosed unit could be made by winding a heating element powered by, for example, a Burgess 4F4H six-volt battery. It should be possible to utilize the heaters to a higher efficiency than at the present time. In such case, it may be possible to get by with ten or 15 watts.

Design of drop recorder--The entire unit was built up around the six-volt, one-rpm motor (see Fig. 1). At this speed some 300 meters of tape would be wound on the take-up reel A in a day's time. Consequently, two reduction gears were used to reduce the speed to a point where about 20 m of tape per day was exposed. The tape, which was coated with methylene blue dye, was 16 mm wide and reasonably water resistant. The reels for the tape were Kodak 16-mm × 100 ft movie reels. After exposure (through opening B, Fig. 1) the tape passed over two 15-watt cylindrical lamps. This insured sufficient drying, even in the heaviest rain, to prevent any smearing of the drop record on the take-up reel.

The entire unit, including battery, was placed within the small metal box C. The rain fell through a 30 × 40-mm opening, thus giving an effective tape exposure area of 6.4 cm^2. As the recorder was designed and used in Hawaiian orographic rains, which are composed mainly of drops less than two mm in diameter, the 6.4-cm^2 area was adequate for the job. However, calibration of the tape showed that a 2.75-mm diameter drop at terminal velocity produced a spot 16 mm in diameter, the width of the tape. Thus, for use in areas where convective type and frontal storms are common, one would have to use a tape of sufficient width to handle raindrops in excess of four mm. A tape width of perhaps 60 mm would be desirable. It would probably be necessary to change the gear ratio to increase the tape speed to some 40 m per day. As the tape is easily treated with the water-soluble methylene blue dye, the added area will pose no problem to the treating process. The optimum values of tape width and speed will depend on the general drop-size distributions in the particular region where the recorder is used.

No attempt was made to drive the tape at constant speed. Time marks were placed on the tape about every ten hours. From these checks and previous laboratory calibrations, a curve of the relationship of time to exposed tape length was made. The time of occurrence of the rain spots on the tape was picked off this curve.

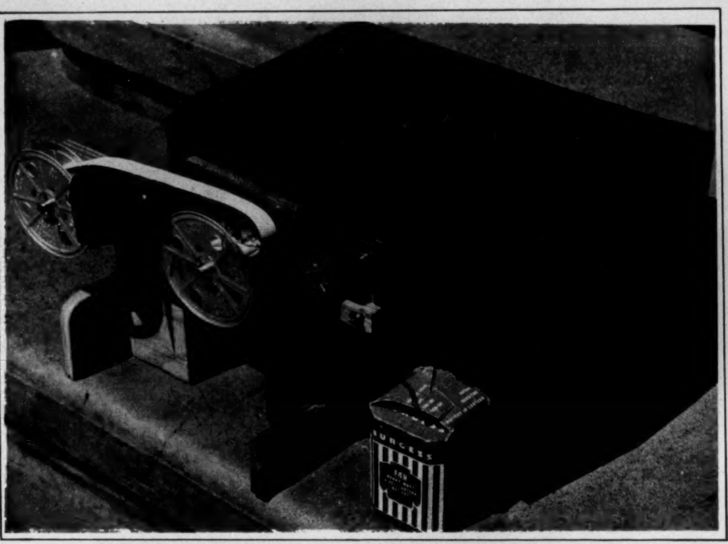

Fig. 1--The raindrop recorder removed from the weather housing

Some results of the drop recorder--During the period June 16-18 and June 25-July 1, 1952, a detailed cloud-physics study was carried out on the island of Oahu, Hawaii, by the Meteorology Department of the Pineapple Research Institute of Hawaii and A. H. Woodcock and the writer, both of the Woods Hole Oceanographic Institution. The primary purpose of this study was to obtain as much detailed information as possible on the formation of cloud and rain on the southern end of the Koolau mountain range. To this end, special attention was given to the sea-salt hypothesis [WOODCOCK, 1952]. It is believed that the orographic rain of Hawaii develops from sea-salt particles which grow initially by condensation and then by accretion. The growth of the salt particles to raindrop size would require considerably more time than is available during the orographic lifting of the cloud. This requires that either rain be falling from the clouds as they pass over the windward shore of the island or that large droplets be present within the cloud. In either case the orographic lifting causes additional condensation of water and should bring about an accelerated growth of the small droplets already present.

Two raindrop recorders were used to determine the percentage of showers on the central part of the island that were preceded by rain to windward. One recorder was located on the windward side of the island (Recorder 1) at the edge of the sea and the other at a point 6.5 miles downwind and in the lee of the 3000-ft Koolau mountain range (Recorder 2). The mean annual rainfall at the position of the first recorder is about 35 inches, increasing to 150 inches at the position of the downwind raindrop recorder.

Both recorders were kept running for seven consecutive days (with the exception of Recorder 1, which was not running on the last day). Although Recorder 1 was not equipped with the drying lamps, the relatively infrequent rain showers were seldom heavy enough to cause extreme flooding of the tape. Some of the interesting characteristics of the orographic rains, as obtained from the tapes, are listed in Table 1. It is seen that Recorder 2 received rain on each of the seven days. Expressed percentagewise (the ratio of the number of hours of rain to the 24 odd hours of tape exposure), the days were increasingly wetter with rain falling 72 pct of the time on June 29-30, 1952.

Table 1--Comparison of data from the two raindrop recorders

Date and time				Rain occurrence[a]		Number of showers		Max. shower duration		Drop-size change[b]		Flooding[c]	
From		To		Rec 1	Rec 2	Rec 1	Rec 2	Rec 1	Rec 2	Rec 1	Rec 2	Rec 1	Rec 2
1952	h m	1952	h m	pct	pct			min	min			pct	pct
June 25	11 38	June 26	09 47	0	0.15	0	2	0	1	0	0	0	0
June 26	10 01	June 27	09 36	4	26	7	14	48	169	1	8	0	23
June 27	09 48	June 28	07 55	14	28	9	22	103	60	3	2	20	63
June 28	08 04	June 29	08 12	4.4	35	10	30	11	60	1	2	52	40
June 29	08 20	June 30	08 34	2.2	72	6	23	17	188	0	12	19	32
June 30	08 48	July 1	08 37	0.3	11	5	13	1	19	0	0	20	20
July 1	08 48	July 2	10 11	. .[d]	15	. .[d]	15	. .[d]	69	. .[d]	1	. .[d]	67

[a] Percentage of exposure time that rain was falling.

[b] Minimum number of marked drop-size variations during maximum shower (during flooding it is impossible to ascertain drop-size change).

[c] Per cent of rainy period that rain intensity was sufficient to cause flooding.

[d] Recorder 1 was not running during the last day.

During the week's run 119 separate showers were recorded. Although many of these showers were separated by intervals as small as five minutes and consisted of only a brief fall of drizzle-type drops, it is interesting to note that two weighing-type rain gages gave no indication of the frequent occurrence of showers. The records of these two recording gages, located about 0.7 mile on either side and nearly on a line normal to the prevailing tradewinds, indicated the passage of 34 and 40 showers respectively. The similarity between the two rain traces makes it reasonable to suspect that this rainfall pattern was similar in the area between the gages and, in particular, at the site of Recorder 2. If this is true, it is apparent that some 70 pct of the showers were not being detected. These discrepancies are no doubt due to the evaporation of the light rain which adheres to the sloped sides of the collectors of the recording gages or to accumulation on the collector of several such rains. In the latter case, the water from these rains will eventually reach the receiver but will be recorded as a single shower. (This is especially true in the light Hawaiian rains. In the course of obtaining rainwater for chemical analysis, the writer used stainless-steel funnels of 0.5 m^2 effective area. On many occasions, ten to 20 minutes would elapse while rain continued to adhere to the hydrophobic surface of the funnel. Only after 100 or more milliliters had accumulated would any pass into the collector bottle.)

In the course of examining the tapes, an arbitrary method of classifying the drop distributions was adopted. Each drop distribution in the showers was listed as having many or few, small drops, large drops, large and small drops, or flooding. Flooding referred to an overabundance of drops which rendered the tape a uniform blue. Fifty-five per cent of the showers were classified as having few drops. These occasions probably represent those in which evaporation on the collector prevented any indication of the rain on the gage. A worthwhile project would be to use a standard recording gage and drop-size recorder side by side. The lack of sensitivity of the gage to brief light rains would then become apparent.

The showers at Recorder 2 lasted from one minute to over three hours. The flooding of the tape, indicative of medium to heavy rain, occurred a maximum of 67 pct of the total time of rainfall. Recorder 1, on the windward side of the island, indicated considerably lower values in nearly every category. The maximum amount of rain, at least as measured by elapsed time, was 14 pct on the third day. During the same time it rained 28 pct of the time at Recorder 2. On June 29-30, Recorder 1 indicated rain only 2.2 pct of the time as compared to 72 pct at Recorder 2. It should not be inferred from this that the majority of the showers completely develop during the time it takes the clouds to travel between the two recorder stations. It seems probable, as already discussed, that many of the clouds have already developed to the drizzle stage by the time they pass over Recorder 1.

Ten sections of the tape records are shown in Figure 2. Tape 1 illustrates the relatively splash-free pattern associated with the larger drops. The spots, some six mm in diameter, indicated raindrops of 1.7-mm diameter. Tapes 2-6 show the large and small drops that represent the low-intensity rains. The low number per sq m is realized when one considers that approximately 2.6 minutes are required for the tape to move the four cm across the exposure opening (see time scale on Tape 1). Tape 7 shows both large and small drops alike. Tape 8 illustrates the wind effect on the small drops. The turbulent nature of the wind is apparent from the varied direction of the

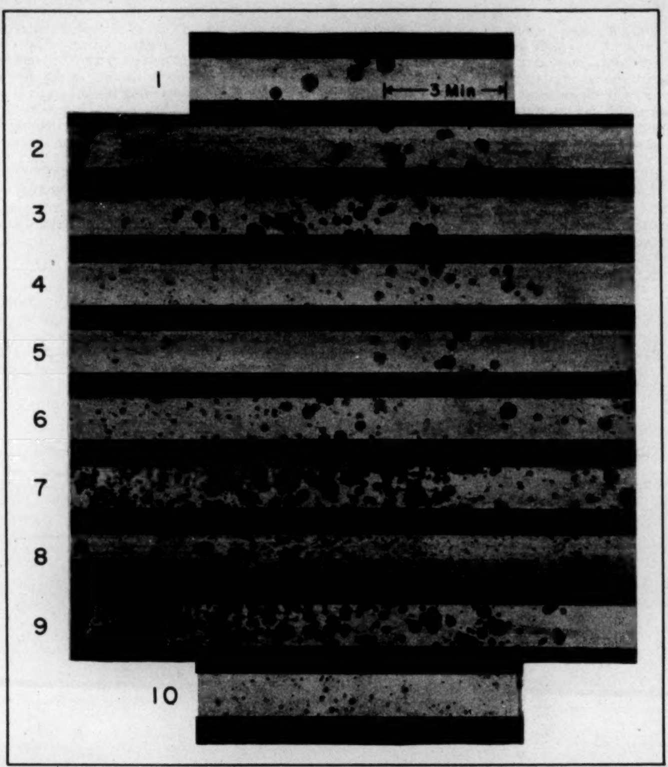

Fig. 2--Raindrop records obtained with the recorder; the initial stage of tape flooding is shown on the left hand end of Tape 9

"tails" of the spots. Tape 9 shows the beginning of a shower. Although relatively few drops fell during the first six or seven minutes, the intensity increased and eventually caused a flooding of the tape. Tape 10 is typical of the fine rain which is so common in the Hawaiian Islands. The drops pictured are <0.7 mm diameter and, as explained earlier, often fail to register on standard rain gages.

Conclusions--The drop recorder has proved quite useful for the purpose for which it was designed. It succeeded in giving a continuous record of the occurrence and duration of showers in Hawaiian rains. It was also possible to obtain the maximum drop size and some idea of the relative frequency of appearance of the smaller drops in light to medium rains.

It is realized that the present drop recorder has many limitations, some briefly touched upon in this paper. For example, there would be considerable doubt as to the accuracy of calculations of the spatial distribution of drops. At the best, they would represent, not point distributions, but distributions averaged over a thousand or more meters of vertical height. A wider tape running at a higher speed would be needed to minimize this problem. The problem of tape flooding in rains of moderate to high intensity could, in all probability, be eliminated by using a horizontally mounted sheet-metal disc as a protective shield for the tape. This disc could be rotated by the tape-drive motor, on an axis normal to its plane, by either pulley or gear drive. A slot cut in the disc would pass over the moving tape for each revolution of the disc. Thus, by varying the disc speed and slot width and distance from the disc axis, a wide choice of exposure times and frequency could be obtained. The intermittent exposures would probably be short enough to prevent flooding in rain of high intensities, and yet be frequent enough to obtain the times of starting and ending of the rain.

In addition to using two recorders as described in this paper, it would be interesting to utilize several such recorders located at intervals along the path of a shower. A similar study would involve locating recorders at points along the fall line of a mountain against which orographically formed rain is falling. In this way the variations in raindrop size from cloud top to bottom could be found.

Acknowledgments--The writer would like to thank his co-worker, Alfred H. Woodcock, who first suggested the possible advantages of a drop recorder in studying Hawaiian rains. He is indebted to W. A. Mordy of the Pineapple Research Institute, Experiment Station of the Hawaiian Sugar Planters' Association, and the Territorial Cattlemen's Council, for the opportunity to work in Hawaii. He is grateful to David Johnson and Laurence Eber, also of the Pineapple Research Institute, for their assistance in obtaining data. This study was supported by the Office of Naval Research under Contract Nonr 79800 (NR-085-001).

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Woods Hole Oceanographic Institution,
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THE RADIOACTIVITY OF BOTTOM SEDIMENTS IN CHESAPEAKE BAY

Gilbert Jaffe and James H. Hughes

Abstract--Very little is known of the natural radioactivity exhibited by continental-shelf sediments off the eastern coast of the United States. A knowledge of the level of this activity is most important if future surveys are to utilize radiometric techniques for the solution of oceanographic problems. Activities were determined for a group of samples from selected locations in the Chesapeake Bay area. The apparatus for making these measurements is described. Results are used to show the distribution of natural radioactivity in this bay.

Introduction--In recent years there has been an increasing interest in the near-shore portion of the continental shelf. A knowledge of the properties of the sediments in this area is becoming more significant both economically and militarily. One of the properties of these "inshore" sediments that has received little attention in the past is radioactivity. While it is commonly known that unconsolidated marine sediments do possess a certain amount of this activity, detailed, quantitative measurements are lacking.

In the future it is quite likely that radiometric tracer techniques will be applied to the study of certain oceanographic phenomena. This will necessitate information concerning the radioactive background of the material dealt with. (Background in this sense is the activity of the sample in its natural state). If ocean sediments are to be considered in this manner, then the background or base-level count will include the activity produced by small amounts of radioactive materials that are present in almost all sediment samples. This investigation was undertaken in order to gain some idea of the intensity of this naturally occurring radioactivity. The samples analyzed are from selected portions of the Chesapeake Bay area and were supplied to the Hydrographic Office by the Chesapeake Bay Institute of the Johns Hopkins University.

Counting device--One of the problems encountered in measuring the activity of sediments that are only weakly radioactive is the enormous amount of time required to reduce the statistical error to a reasonable amount. This is especially true if, in order to obtain good reproducibility, a standard size planchet (one inch in diameter, 5/16 inch in depth) is used to hold the sample in a conventional lead-lined sample holder containing an end-window Geiger-Müller tube. The background count at the Hydrographic Office, using such apparatus, was, in general, about five times greater than that found in the sample. This necessitated a long counting time and made the apparatus impractical because of the limited time available for the study.

Three changes were considered in an effort to improve the count ratio. First, the background could be reduced by incorporating an anticoincidence circuit into the counter system. This possibility was discarded because it involves a considerable amount of electronic equipment and time in order to build and adjust the circuit. A second possible change was the employment of materials of a high atomic number, like lead, in the construction of the planchet. Such materials reflect a portion of the ionizing particles back into the counter, a process known as back-scattering. This change, though easily accomplished, did not give sufficient increase in count when actually tried. A third possible change, and the one finally adopted, was the substitution of a thin-walled Geiger-Müller tube for the end-window type. Using this method, which is described in detail below, it was possible to increase considerably the quantity of sample that is in contact with the sensitive portion of the counter. As a result the counting ratio was not only changed from 5/1 but also reversed to 1/2 for most samples. This made it possible to reduce the counting time sufficiently so that a representative number of samples could be analyzed in the time available.

The counter unit was constructed with a 30 mg/cm^2, thin-walled Geiger-Müller tube having a 25 pct transmission for beta-ray spectra of Emax. 350 kev. A section of glass tubing was fitted concentrically around the Geiger-Müller tube (see Fig. 1). Both tubes were held in a vertical position and stoppered at the base. The sediment sample was poured between the two tube walls to a specified height while the counter assembly was tapped to insure maximum packing of the sample. This unit was connected to a commercial scaler which records the number of impulses that reach its input amplifier.

Table 1--Radioactivity of the samples

Sample	Net counts per minute	Sample type
1	52.5	Silt and clay
2	62.3	Silt and clay
3	10.5	Sand
4	57.5	Silt and clay
5	40.2	Fine sand
6	43.7	Fine sand
7	54.9	Fine sand
8	50.1	Silt and clay
9	30.1	Fine sand
10	16.3	Sand
11	31.8	Silt and clay
12	45.6	Fine sand
13	39.2	Sand
14	35.3	Fine sand
15	40.1	Fine sand
16	48.6	Silt and clay
17	45.2	Fine sand
18	8.0	Sand
19	38.2	Fine sand
20	41.3	Fine sand
21	43.4	Sand
22	35.8	Sand
23	26.1	Sand
24	38.6	Fine sand
25	9.1	Sand
26	30.1	Fine sand
27	36.1	Silt and clay
28	44.9	Silt and clay
29	37.8	Silt and clay
30	36.8	Silt and clay
31	12.7	Silt, clay and sand
32	38.4	Silt and clay
33	32.8	Sand
34	45.2	Silt and clay
35	36.7	Silt and clay
36	50.6	Silt and clay
37	15.4	Sand
38	37.5	Sand
39	35.1	Sand
40	20.1	Silt, clay and sand
41	38.1	Sand
42	33.5	Sand
43	42.0	Sand
44	38.7	Sand
45	41.4	Silt and clay
46	44.0	Silt and clay
47	39.4	Fine sand
48	38.4	Fine sand
49	36.3	Fine sand
50	38.2	Fine sand
51	39.1	Fine sand
52	23.8	Sand
53	40.2	Fine sand
54	35.7	Fine sand
55	36.8	Silt, clay and sand
56	13.1	Coarse sand
57	57.0	Silt, clay and sand
58	14.7	Coarse sand

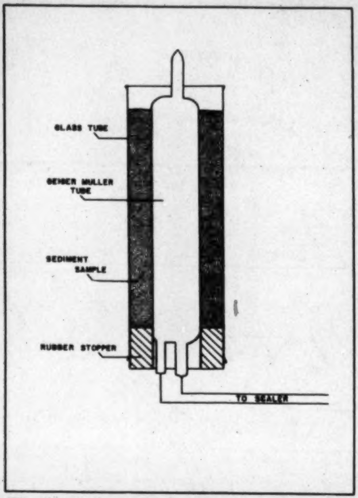

Fig. 1--Cross section of the counter assembly

The geometric reproducibility of this counting unit is probably not as good as that obtained with a commercial sample holder, one of which has a 0.1 pct reproducibility. However, the substantial reduction in total counting time more than compensates for the reduced accuracy. The preliminary nature of this investigation permitted use of the relatively simple apparatus described. No attempt was made to distinguish between the various types of nuclear particles entering the counting chamber or their energies.

Samples--A gravity-type coring device was employed to obtain the original samples from which portions were taken for analysis. The top six inches of each core was quartered until an amount of material sufficient to fill the sample holder (about 55 grams) remained. With the exception of drying and gently disaggregating, the samples were not treated in any way. Therefore, the measurements indicate the radioactivity of the mineral grains, the organic material, and the salts that are present as a result of the natural water evaporation.

The sediment classification as sand, fine sand, or silt and clay was determined by a macroscopic inspection of the prepared sample. In the future it is hoped that detailed size analyses of these same samples will be available. This will enable a more exact comparison to be made.

The locations of the cores are shown in Figure 2. It should be emphasized that while the entire core is generally several feet in length, the results of this study are valid for the top six inches only. It is hoped that an investigation of the activity of the entire length of the core can be conducted at a later date.

Probable statistical error--The counting time devoted to each sample was such that the probable statistical error was less than five per cent for all determinations. For the most part this could be accomplished in one hour or less.

Results--Net counts per unit time is probably the most convenient method of stating total radioactivity as determined by the method described. Sample activities are reported on this basis. Often the practice is to analyze for radium and report grams of radium per gram of sample. This, however, does not give a true picture of the total activity for there are often small quantities of uranium, thorium, potassium 40, and other radioactive elements present in the sample. Detailed chemical analyses of the bottom samples herein reported were not carried out. Therefore, it is not known which radioactive element, or elements, is producing the total activity.

The activity of each sample is tabulated in Table 1. An inspection of the relationship of the radioactivity to the type of sediment reveals a definite correlation between the two. The arithmetic mean for the sands is 28.6 counts per minute, for the fine sands 39.5 counts per minute, and for the silts and clays 44.7 counts per minute. This dissimilarity was at first believed to be the result of sample packing which would vary with grain size. In order to obtain some experimental evidence on this point, several samples that had been previously tested were crushed to a finer state and re-analyzed. The change in count for each sample did not vary by more than the allowable statistical error. This relationship is similar to that found by UTTERBACK and SANDERMAN [1938] who analyzed 16 clay samples and eight sand samples for radium by the radon method. The average for the sands was 0.2×10^{-12} g Ra/g and for the clays 0.37×10^{-12} g Ra/g. The radon method is independent of the sediment grain size, so that size alone is not responsible for varying activity.

As a result of this earlier work and the present experiments it seems logical to assume that any difference in the radioactivity of these samples is directly related to the quantity of radioelements that are present in them.

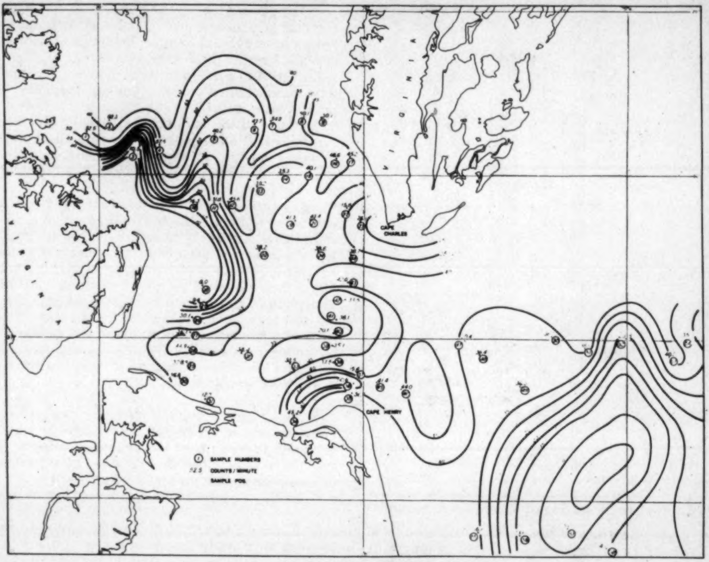

Fig. 2--Chart of lower Chesapeake Bay

The distribution of activity in the sediments of lower Chesapeake Bay is apparently independent of nearness to shore or to water depth. Two factors that probably do have a strong influence upon the activity are the source and the adsorption qualities of the sediments.

To illustrate the former, granite generally has several times the radioactivity of sandstone. Therefore, a sediment derived from a granitic area would be expected to have a greater activity than one from a sandstone source. The adsorption factor is evidenced by the clay minerals which have a far greater capacity for adsorbing ions in solution than the sands do. Thus, if a sediment composed largely of clay minerals passes through a body of water containing easily adsorbed ions, it would be expected to pick up a considerably greater number of ions than a sand body under the same conditions. The radioactive ions adsorbed in this fashion would add substantially to the total count of the sample.

The factors already mentioned seem to explain, at least in part, the lack of pattern shown by the distribution of activity in lower Chesapeake Bay. Areas of high and low activity are scattered throughout the Bay (see Fig. 2). The only obvious trend is exhibited by the relationship of the activity to the sediment type. The finer sediments have the higher, average radioactivity.

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Office of Naval Research, Washington 25, D. C.

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OCEANOGRAPHIC RESULTS OF PROJECT SKIJUMP I AND SKIJUMP II IN THE POLAR SEA, 1951-1952

L. V. Worthington

Abstract--Oceanographic observations made from ice floes by United States naval aircraft in 1951 and 1952 indicate that the circulation of the Polar Sea is more complicated than the cyclonic system suggested by Nansen. The chief feature observed is a large anticyclonic eddy north of Alaska. Some evidence is produced of the existence of a submarine ridge running across the center of the North Polar Basin.

Introduction--Project Skijump I was inaugurated in 1951 by the Office of Naval Research to study the oceanography of the Polar Sea, using aircraft. During the spring of 1951 a Navy R-4D was used. Twelve landings were made on the ice and three hydrographic stations were occupied. During that season the area studied was limited by the range of the R-4D.

For the season of 1952 two Navy P-2V aircraft were added to the R-4D. These planes were capable of landing on the ice and refueling the R-4D, and it was thought that the oceanographic survey could be extended much farther from the base at Point Barrow, Alaska. The positions of the hydrographic stations made in both years are illustrated in Figure 1. Stations 1, 2, and 3 were made on April 1, April 21, and May 3, 1951.

Stations 4, 5, and 6 were made on successive days (March 11-13, 1952), with the R-4D remaining on the ice during the nights of March 11 and 12 and a P-2V coming out to her from Point Barrow each day.

Station 7 was made on March 25, the R-4D remaining on the ice as before. The following day the R-4D and a P-2V landed at station 8; the P-2V refueled the R-4D and returned to Point Barrow. The hydrographic station was made during the night of March 26. On the morning of March 27 the R-4D's port landing gear collapsed in an attempt to take off and she had to be abandoned. This concluded the oceanographic section of Skijump II. With the plane it was necessary to abandon the winch, the Nansen bottles, and much other equipment. The best operating month from the point of view of light, ice conditions, and air temperatures is April, which was lost on account of this misfortune.

Methods--The technique of making hydrographic stations from a plane is unusual and may, therefore, be worth going into in some detail. The holes through the ice were made with a 5-hp, gasoline-driven, post-hole digger. This machine bored a clean 12.5-inch hole through five feet of ice in about ten minutes. This diameter was found to be large enough for Nansen bottles. The chain-saw and ice-chisel method used in 1951 took as much as 2 1/2 hr for ice of the same thickness.

Analysis of salinity samples taken in 1951 showed that some had been frozen, causing highly saline water to settle to the bottom of the Nansen bottle, where it was drawn off into the sample bottle. Accordingly, in 1952 every effort was made to see that the Nansen bottles were not exposed to freezing temperatures. The plane, when on station, was heated by a gasoline-burning space heater which was kept running continuously a few feet from the plane. The heater had three ducts, two of which were brought into the plane through one of the ports while the third was directed to the top of the ice hole. A tent surrounded the hole enclosing it with the interior of the plane. The heater kept the top of the hole free from slush ice at all times during the station work.

The after part of the plane where the Nansen bottles were racked was kept as near 5° C as possible, enough to preclude freezing but not so much as to necessitate a long wait for the thermometers to reach equilibrium. Comparisons of paired thermometers were made during the last two stations with the results (excluding one defective thermometer) shown in Table 1.

Table 1--Comparison of paired thermometers

Difference in corrected temperature	Number of observations
°C	
0.00	7
0.01	10
0.02	1
0.03	1
Total	19

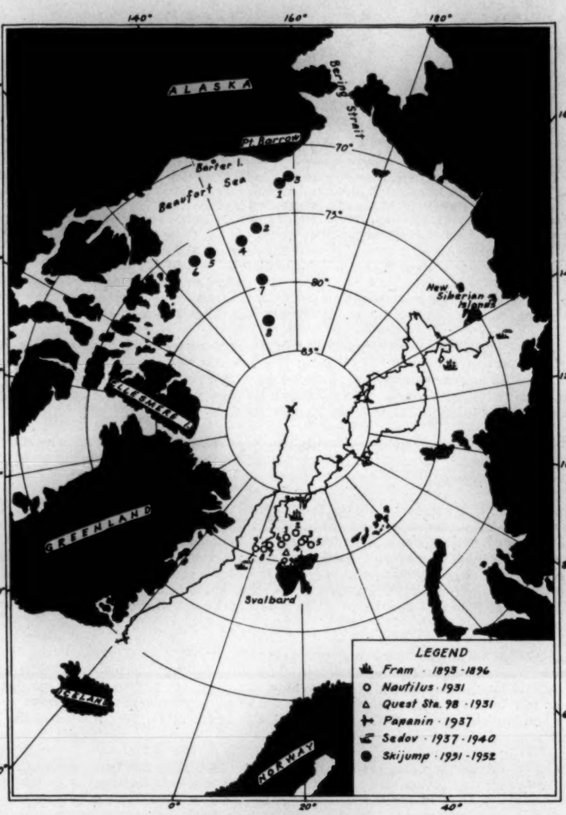
140°
160°
180°
120°
160°
ALASKA
Bering Strait
Pt Barrow
70°
Barter I.
Beaufort Sea
1
3
75°
2
4
100°
5
6
140°
7
80°
New Siberian Islands
8
85°
80°
120°
ELLESMERE I.
60°
100°
GREENLAND
1
2
3
4
5
6
7
8
80°
40°
Svalbard
ICELAND
NORWAY
60°
20°
0°
20°
40°
LEGEND
Fram · 1893-1896
○ Nautilus · 1931
△ Quest Sta. 98 · 1931
Papanin · 1937
Sedov · 1937-1940
● Skijump · 1951-1952

Fig. 1--Expeditions on which oceanographic measurements were made in the deep Polar Basin

The winch was mounted forward owing to its weight, but the observer had a clutch control aft which enabled him to bring the bottles to hand smoothly in most cases. The winch held 3400 m of 1/16-inch 7 × 7 stainless steel cable with a breaking strain of 480 lb. A strip of friction tape was wrapped around the wire before each bottle was attached to adapt the small diameter wire to the clamp on the bottle. As only one bottle slid down the wire, this procedure is regarded as satisfactory. A 15-lb weight was used at the end of the wire, and all wire angles were nearly zero. On all shallow series the wire was moved up and down by hand for a few seconds to ensure proper flushing of the bottles.

The results were somewhat marred by a Nansen bottle which became defective at Station 7 and did not close properly. This escaped detection until the samples were titrated in Woods Hole.

Table 2--Hydrographic station data

Date	Station	Location		Depth	Temperature	Salinity
		Lat. N	Long. W			
1951		° ′	° ′	m	°C	o/oo
Apr. 1	1	72 52	156 32	2	-1.64	30.26
				10	-1.56	. . . .
				20	-1.30	30.10
				50	-0.92	30.09
				100	-1.51	31.87
				200	-1.20	. . . .
Apr. 21	2	75 45	150 00	2	-1.58	29.72
				10	-1.61	29.70
				20	-1.60	. . . .
				50	-1.52	29.50[a]
				100	-1.21	31.96
				150	-1.49	32.55
				200	-1.48	33.53
				300	-0.07	34.47
				400	0.36	34.77
				600	0.37	34.72[a]
				800	0.10	34.85
				999	-0.06	34.70[a]
				1295	-0.26	. . . .
				1594	-0.38	. . . .
				2092	-0.42	. . . .
				3200	(bottom, by sounding)	
May 3	3	72 36	158 32	2	-1.64	30.78
				10	-1.68	30.77
				20	-1.68	30.78
				50	-1.68	31.83
				100	-1.77	32.56
				150	-0.38	34.39
				171	(bottom, by wire)	
1952 Mar. 11-12	4	76 25	144 19	2	-1.60	29.34
				10	. . . .	29.31
				25	-1.62	. . . .
				50	-1.15	30.03
				75	-1.15	31.78
				100	-1.25	. . . .
				150	-1.46	32.80
				200	-1.45	. . . .
				300	-0.15	33.95
				500	0.52	34.70
				600	0.38	34.86
				800	0.16	34.92
				1300	-0.22	34.90
				1700	-0.37	34.94
				2200	-0.52[a]	34.92
				3000	-0.35	34.99
Mar. 12	5	76 26	134 00	2	-1.64	30.03
				10	. . . .	30.02
				25	-1.65	30.03
				50	-1.72	31.37
				75	-1.63	31.70
				100	-1.34	32.40
				150	-1.49	33.01
				200	-1.07	33.90
				400	-0.35	34.79

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[a] Questionable.

(Continued)

Table 2--Hydrographic station data (concluded)

Date	Station	Location		Depth	Temperature	Salinity
		Lat. N	Long. W			
1952		° ′	° ′	m	°C	°/oo
Mar. 12	5	76 26	134 00	500	0.51	34.85
				700	0.14	34.87
				1000	. . . .	34.88
				1300	-0.20	. . . .
				1700	-0.36	34.93
				2100	-0.42	34.96
Mar. 13	6	76 20	128 20	2	-1.64	30.38
				10	-1.66	30.41
				25	-1.68	30.49
				50	-1.61	31.51
				75	-1.31	32.11
				100	-1.45[a]	32.71
				150	-1.45	33.40
				200	-0.74	34.32
				300	0.12	34.71
				400	0.39	34.83
				500	0.39	34.87
				600	0.27	34.87
Mar. 25	7	79 36	147 10	2	-1.60	29.33
				10	-1.59	. . . .
				25	-1.61	29.31
				50	-1.21	30.59
				75	-1.03	31.73
				100	-1.21	32.20
				150	-1.48	32.85
				200	-1.35	33.62
				300	-0.10	34.46
				400	0.44	. . . .
				500	0.56	. . . .
				600	0.41	34.86
				700	0.24	34.87
				1000	-0.10	35.02[a]
				1400	-0.25	34.94
				1800	-0.37	. . . .
				2300	-0.41	34.96
				2950	(bottom, by sounding)	
Mar. 26-27	8	82 22	145 20	3	-1.68	30.44
				25	-1.67	30.60[a]
				51	. . . .	30.34
				75	-1.34	31.89
				100	-1.31	32.57
				150	-1.45	33.00
				200	-1.27	33.86
				300	-0.09	. . . .
				400	0.30	34.79
				500	0.43	34.85
				600	0.31	. . . .
				800	0.11	34.99[a]
				1000	-0.12	34.88[a]
				1500	-0.30	. . . .
				2100	-0.42	. . . .

[a] Questionable.

There were other cases of pollution that could perhaps have been avoided by a more rigorous testing of Nansen bottles. A tabulation of the hydrographic station data is given in Table 2.

Oceanography--The deep Polar Basin was discovered by Nansen in 1893 in his historic expedition aboard the *Fram* [NANSEN, 1902]. The *Fram* was deliberately allowed to be frozen into the ice field, and drifted during the years 1893-1896 from a point north of the New Siberian Islands across the eastern half of the basin to a point north of Svalbard, where she got free of the ice.

The submarine *Nautilus* attempted to penetrate the Polar Sea beneath the ice in 1931 [SVERDRUP and SOULE, 1933]. She was prevented from submerging by the loss of a diving plane and was thus limited to a small but most interesting area north of Svalbard.

In 1937 a Russian expedition under Papanin landed a plane on the ice close to the pole and drifted, in the course of 274 days, out of the Polar Sea. The expedition was taken off its ice floe by ship after it had been carried to latitude 71° N by the East Greenland Current.

In 1937-1940 the Russian icebreaker *Sedov* roughly paralleled the *Fram's* track. Complete published data from the two Russian expeditions are not available, but WÜST [1942] was able to piece together some information from various sources including the Russian newspapers. The tracks of these expeditions together with the positions of Skijump's stations are shown in Figure 1. A further expedition in the *Maud* [SVERDRUP, 1929] attempted to drift across the Polar Sea in 1922. This was certainly the best-equipped expedition to set out, but by great misfortune the *Maud* was unable to penetrate the deep Polar Basin, being confined by adverse ice drift to the waters of the Siberian Shelf.

What is known of the general character of the Polar Sea has been derived from those expeditions. The surface water is cold (-1.5° to -1.9° C) and of low salinity (29 to 33 °/oo). This water is formed in the basin itself and is called North Polar water [NANSEN, 1902].

Beneath the surface water is a transition layer (of varying thickness) to Atlantic water. This water enters the basin to the west of Svalbard with temperatures up to 4° and salinities of slightly more than 35 °/oo. A wedge of Atlantic water with temperatures greater than 0° has been observed at all deep stations in the Polar Sea. The deeper 0° isotherm is found between 700 and 900 m, and provides a convenient lower boundary for this water.

Below the Atlantic water is found the Polar Deep water. This water is formed in the Norwegian Sea and consists chiefly of Atlantic water with a slight admixture of North Polar water. As it enters the basin near Svalbard it has a slightly lower salinity than the intermediate water, about 34.94 °/oo. Winter conditions in parts of the Norwegian Sea render the whole water column isothermal at temperatures below -1°, forming Norwegian Sea deep water which is nearly identical with Polar deep water.

North Polar water--Nansen considered that the freshness of the North Polar water was maintained by the inflow of fresh water from the great Siberian rivers, and to a lesser extent by the precipitation over the Polar Sea. He based this on salinity values that increased steadily in the surface layer as the *Fram* drifted away from the Siberian Shelf. It appears from Skijump data that the freshness of the surface layer depends more upon distance from the source of saline water than upon proximity to the Siberian coast. Skijump Stations 4 and 7 had lower salinities (29.34 and 29.32 °/oo) than any of those observed along the *Fram's* drift except on the Siberian Shelf itself.

From evidence found in the Atlantic water, Station 4 is judged to be in the center of an eddy and is thus farther in point of time from the source of saline water than any other station yet made in the Polar Sea. In Figure 2 the surface salinities found in Skijump are plotted and the 30 °/oo isohaline sketched in.

Atlantic water--As the warmer, more saline Atlantic water flows into the Polar Sea, it submerges beneath the North Polar water. Upon entering near Svalbard it has a maximum temperature of more than 4° at 50 m [*Quest* Sta. 98, in Fig. 1 of MOSBY, 1938]. As it progresses farther into the basin, its maximum temperature diminishes and is found at greater depths.

The lowest observed maximum in the Polar Sea, +0.32°, was found by Nansen at 81°30'N, 125° E, at a depth of 400 to 500 m. Nansen's maxima increased steadily from this point as the *Fram* drifted toward Svalbard. Nansen's theory of the Atlantic water circulation was based on these maxima. He concluded, lacking observations from the western half of the basin, that the Atlantic water revolved cyclonically around the perimeter of the basin, gradually losing heat, and that the maxima on the Canadian-Alaskan side would fall below 0°. Nansen's conception is confirmed, at least in the neighborhood of Svalbard, by the results of the *Nautilus* cruise, where it is

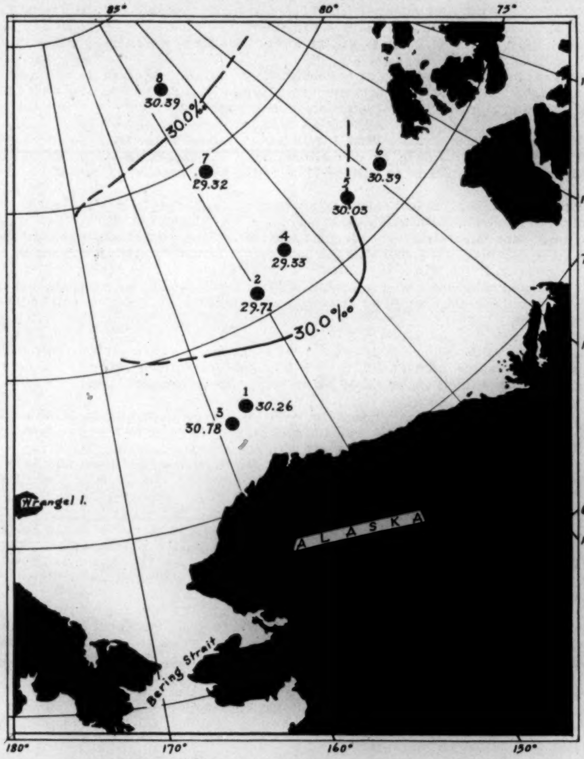

Fig. 2--Salinity ^{o}/oo of the surface layer, Skijump 1951-1952

stated: "This distribution indicates that the greater part of the Atlantic water follows the border of the shelf towards the northeast, but a weaker branch runs toward the northwest. . ." [SVERDRUP and SOULE, 1933].

That Skijump maxima ranged between +0.39° and +0.52° does not in itself contradict Nansen's theory since large variations in the maxima have been found in different years at nearly the same locations. For example, the Fram's maximum at Station 26, 84° 06′N, 12° 26′ E, was +0.93°, while Sedov's maximum at 83° 59′N, 9° 02′ W, is 1.2. Thus, it is not possible to use the temperature maxima from the different expeditions as an index of water circulation.

What does complicate Nansen's circulation picture is the anticyclonic eddy north of Alaska indicated by Skijump stations. Dynamic computations show water transports relative to the 600-decibar surface of 3.75×10^6 m^3/sec flowing southward between Stations 4 and 6 and 2.66×10^6 m^3/sec flowing eastward between Stations 4 and 8. A tentative system of Atlantic water circulation is illustrated in Figure 3, in which Nansen's picture is modified to include the eddy; clearly, however, other interpretations are possible.

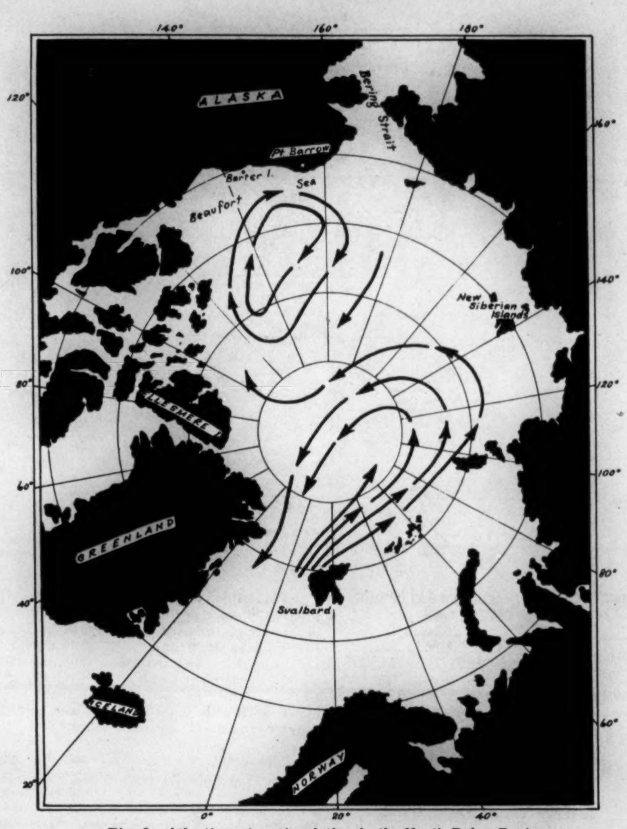
140°
160°
180°
120°
160°
ALASKA
Bering Strait
Pt Barrow
Barter I.
Beaufort Sea
100°
140°
New Siberian Islands
80°
120°
ELLESMERE I
60°
100°
GREENLAND
80°
40°
Svalbard
ICELAND
60°
NORWAY
20°
0°
20°
40°

Fig. 3--Atlantic water circulation in the North Polar Basin

A further phenomenon observed in Skijump was a small negative thermal gradient between 50 and 150 m. Two temperature curves showing this condition are drawn in Figure 4. The gradients appear to be the last remnants of a seasonal thermocline. It is judged that a seasonal thermocline can only have been formed in the Beaufort Sea, which was extraordinarily ice-free in the summers of 1950 and 1951. The gradient was most marked on Station 7 and least marked on Stations 5, 6, and 8.

Table 3 shows the temperatures at the top and bottom of these negative gradients, together with the difference between them. The slightly warmer water is apparently carried by the eddy into areas which are covered with ice even in midsummer. The large gradient found at Station 7 is not surprising when it is considered that, apart from Station 1, Station 7 is the closest station to the southern Beaufort Sea in terms of water transport.

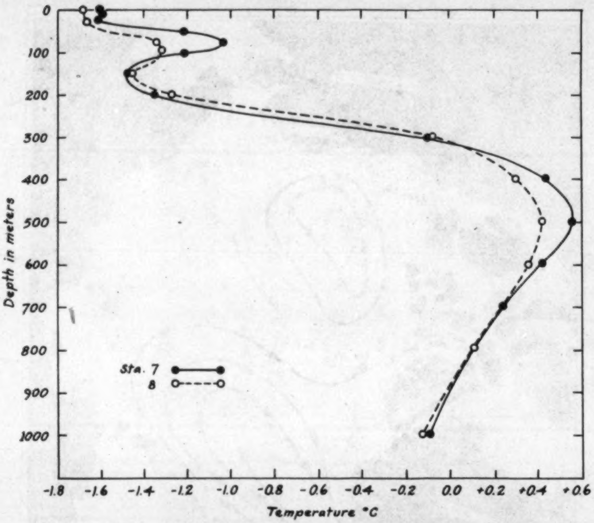

Fig. 4--Two temperature curves showing remnants of a summer thermocline (75-150 m)

Table 3--Temperature at top and bottom of negative gradients

Station	Temperature		
	Top	Bottom	Difference
	°C	°C	°C
1	-0.92	-1.51	0.59[a]
2	-1.21	-1.49	0.28
3		No gradient	
4	-1.15	-1.46	0.31
5	-1.34	-1.49	0.15
6	-1.31	-1.45	0.14
7	-1.03	-1.48	0.45
8	-1.31	-1.45	0.14

[a] Possibly false.

Polar Deep water--Previous sources, *Fram* in 1893-1896 and *Nautilus* in 1931, have agreed that the minimum temperature in the Polar Deep water lies between -0.79° and -0.91°. The colder values are found near Svalbard where the deep water flows in, and the warmer towards the easterly end of the *Fram's* drift. The minimum was found by Nansen between 2500 and 3000 m, below which depth the water becomes adiabatically warmer.

The minimum temperature found in Skijump stations was -0.52° at 2200 m on Station 4. There are in fact indications that this figure is low due to misreading or malfunction of the thermometer. The thermometer in question was malfunctional on the next series and was not used subsequently. If we accept the reading of -0.52°, we must accept a positive gradient of 0.17° between 2200 and 3000 m, a value considerably over the adiabatic rate.

On this basis it appears that the probable temperature minimum in the Beaufort Sea is about -0.45° at 2300 m. This value is 0.34° higher than any minimum previously recorded. Further, since the adiabatic heating starts at a shallower level than in Nansen's observations, it seems likely that Beaufort Sea bottom temperatures are as much as 0.50° warmer than those on the other side of the basin.

There are two possible explanations for this: (1) The deep water entering the basin from the Norwegian Sea has been warmer in recent years than it was in Nansen's time, and (2) there is a submarine ridge, running roughly from Ellesmere to the New Siberian Islands, which separates the deepest water of the Beaufort Sea from the remainder of the basin.

In support of the former hypothesis is the overall weakening of the severity of the Arctic climate as reflected in the intermediate water by the temperature maxima observed by the Sedov, which are higher in the same location than those observed by the Fram, as noted above.

In support of the latter hypothesis are the observed temperatures in the deep water. Nansen's nearest deep observation to Svalbard shows a temperature of -0.87° at 3000 m. This agrees perfectly with the deep temperatures found on the Nautilus expedition, which range between -0.82° and -0.91° in the 2000 to 3000 m level. This, however, does not prove that changes have not taken place between 1931 and the present.

There is some indication that soundings give further support to the existence of a ridge. CRARY and Others [1952] found depths up to 3838 m in the Beaufort Sea (74° 45′ N, 150° 55′ W). On Skijump Station 7 about 300 miles to the north the depth had diminished to 2950 m. Unfortunately, no sounding was obtained on Station 8, but the depth was in excess of 2100 m by wire.

The sill depth of the ridge should not exceed 2300 m, the depth of the temperature minimum, below which the water is homogeneous or very nearly so. It is not possible on the basis of present observations to estimate how shallow a ridge could be.

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THE INFLUENCE OF GROUND-WATER STORAGE ON THE RUNOFF IN THE SAN BERNARDINO AND EASTERN SAN GABRIEL MOUNTAINS OF SOUTHERN CALIFORNIA

Harold C. Troxell

Abstract--The steep and rugged mountains of Southern California contain considerable ground-water storage. A large portion of the runoff is seepage from this storage. The variations in runoff distribution depend on the geology, physiography, and soil cover of these mountain areas.

Introduction--It is the intent of this paper to indicate in a rather general manner a few of the less understood influences affecting the runoff characteristics in the San Bernardino and eastern San Gabriel Mountains of San Bernardino County. These mountain areas are an integral part of coastal east-west range roughly paralleling the coastline about five to 40 miles inland from the Pacific Ocean and known locally as the Sierra Madre. About six per cent of these mountain areas are above 8000 ft in altitude, 33 pct above 6000 ft, and 71 pct above 4000 ft. In general, these mountains are quite steep and rugged, with average basin-wide land-surface slopes ranging from 15 to 78 pct. The drainage areas are generally small, ranging in size from several miles to seldom more than about 200 sq mi.

The position of these mountain areas across the path of the incoming maritime air has considerable influence on the magnitude and distribution of the precipitation. Consequently basin-wide average annual precipitation ranges from 18 to 42 inches depending on exposure and altitude. Observational data show that only from about two to about 19 inches of this precipitation leaves the area as runoff, the remainder being largely consumed by evaporation and transpiration. Because of the limited yield, it is the desire of each investigator and water user, if possible, to improve the distribution and volume of the supply of water from this source.

The infiltration of precipitation into the mantle rock of these areas and the subsequent influence of outflow from ground-water storage is not always fully understood because of the complexities of the physiography and geology and their influence on ground-water hydraulics. The rocks in these mountains include igneous, metamorphic, and sedimentary types, and, quoting from an unpublished communication from H. V. Peterson,

> In age they range from Recent to Paleozoic and older; in texture from felsites and crystalline sediments where the constituent minerals cannot be distinguished microscopically to gravels containing boulders several feet in diameter. In many parts of the area, particularly near faults and in fault zones, the indurated rocks have been fractured and broken to a remarkable degree; but in other localities where jointing and fracturing is of only ordinary intensity the rocks retain much of their original structure with little alteration and with a paucity of openings. Soils and other weathered products derived from the slow disintegration and decompositions of these rock types are likewise variable in character and composition. Some are coarse, granular, and porous; others which contain a high percentage of silt and clay are dense and impervious. It is thus obvious that the hydrologic characteristics of streams draining from the area can vary between wide limits depending on the properties of the underlying formation, specifically on its capacity to absorb, store, and transmit water falling on the surface.

Types of runoff--Runoff records, available since 1896 in parts of these mountain areas, are sufficiently complete so that by analysis of the streamflow it is possible to separate the runoff as to its immediate origin, either as direct runoff or ground-water runoff. Direct runoff is considered to be that portion of the precipitation occurring at rates in excess of the rates of infiltration and that consequently would find outlet to the nearest stream channel as overland flow. The rates of infiltration of the coarse mantle rock covering these steep and rugged mountain areas are generally very much greater than found in the finer soil mantles of the foothills and valley floor areas.

Table 1--Rates of precipitation and runoff observed during the storm of February 27 - March 4, 1938, in the Fern Canyon area

Duration	Fern Canyon 1/40-acre runoff plots				Fern Canyon drainage areas		
	Maximum observed rate of precipitation	Rate of runoff			Maximum observed rate of precipitation	Drainage area 3 (53 ac)	Drainage area 2 (40 ac)
		Plot 349	Plot 341	Plot 345			
hr min	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr
0 10	1.56	0.0186	0.0198	0.0086	. . .	. . .	. . .
0 15	1.52	0.0186	0.0176	0.0065	1.62	0.33	0.69
0 30	1.36	0.0176	0.0121	0.0055	1.53	0.32	0.67
1 0	1.35	0.0162	0.0101	0.0050	1.48	0.31	0.65
2 0	1.26	0.0159	0.0109	0.0048	1.44	0.31	0.61
3 0	1.20	0.0143	0.0098	0.0047	1.35	0.29	0.60
6 0	0.98	0.0107	0.0086	0.0036	1.10	0.24	0.52
12 0	0.79	0.0083	0.0056	0.0027	0.89	0.16	0.37
18 0	0.81	. . . . .	. . . . .	. . . . .	0.68	0.12	0.29
24 0	0.48	. . . . .	. . . . .	. . . . .	0.54	0.10	0.24
Totals in inches for period	20.44	0.17	0.08	0.06	23.0	3.67	8.80

An excellent demonstration of these high rates of infiltration has been obtained from a series of test plots and small drainage areas in the Fern Canyon area of the San Gabriel Mountains during the flood-producing storm of February 27 to March 4, 1938. These plots and small drainage areas are within the San Dimas Experimental Forest, an area set aside by the United States Forest Service for extensive studies dealing with the influence of forest cover on water supply. The records of precipitation and runoff are given in Table 1 for three of a group of nine undisturbed chaparral-covered plots, and for two of the small drainage areas [TROXELL, 1942, p. 167]. The plots are at an altitude of about 5000 ft and have a slope of about 60 pct. The soil mantle on the plots is about one foot thick and overlies a badly fractured bedrock. The nearby Fern Canyon Watersheds 2 and 3 are small natural drainage areas of 0.063 and 0.084 sq mi respectively, having land slopes of about 65 pct, also with a shallow soil mantle overlying a badly fractured bedrock and supporting a heavy growth of chaparral.

During the maximum 15-minute period of this storm and flood an average rate of precipitation of 1.52 in/hr produced rates of runoff ranging from 0.0065 to 0.0186 in/hr, representing 0.4 to 1.2 pct of the precipitation. The runoff thus measured represents the direct overland type of runoff from these plots. In the nearby Fern Canyon drainage areas the average rate of runoff for the maximum 15-minute period amounted to 0.33 and 0.69 in/hr, but the maximum rate of runoff did not appear at the gaging station until several hours after the occurrence of the maximum precipitation rates. In this instance the maximum rate of runoff amounted to 21 and 43 pct of the maximum rate precipitation. This difference between the runoff from the plots and that from the small drainage areas is believed to be a measure of the subsurface or ground-water contribution to the flood runoff.

On the basis of the entire storm period of February 27-March 4, 1938, a precipitation of 20.44 inches on the runoff plots produced a direct runoff of 0.06 to 0.17 inch, or less than one per cent of the precipitation. In contrast, the Fern Canyon drainage areas produced a runoff of 3.67 and 8.80 inches during this six-day period from a storm precipitation of 23.0 inches. This very much greater runoff amounting to 16 to 38 pct of the storm precipitation is further evidence of a substantial ground-water contribution even during the flood-runoff period.

By way of supplement, Table 2 gives the annual precipitation and runoff observed during the 11-year period of 1935-1946 for the Fern Canyon and Tanbark plots as well as the inflow into San Dimas Creek Flood-Control Reservoir all within and an integral part of the San Dimas Experimental Forest [ADAMS, EWING, and HUBERTY, 1947]. The Tanbark plots represent a group of nine chaparral-covered 1/40-acre plots having an average land surface slope of about 35 pct at an altitude of 2800 ft. For this 11-year period the average annual runoff of the Tanbark plots amounted to 0.1 inch while the nine Fern Canyon plots gave an average annual runoff of 0.4 inch. In contrast the 16.2 sq mi San Dimas Creek drainage area, in which both the Tanbark and Fern Canyon plots are located, gave an average annual runoff of 5.9 inches over the entire area. Consequently, it is believed that in some mountain areas the direct runoff represents only a small part of the basin runoff.

Table 2--Precipitation and runoff within the San Dimas Experimental Forest

Season	Fern Canyon plots		Tanbark plots		Inflow into San Dimas Creek Flood-Control Reservoir
	Precipitation	Runoff	Precipitation	Runoff	
	inch	inch	inch	inch	inch
1935-36	25.0	0.3	22.0	0.2	1.3
1936-37	44.1	0.4	41.0	0.1	7.3
1937-38	52.4	0.3	45.1	0.5	14.4
1938-39	22.0	1.4[a]	20.2	0.0	2.5
1939-40	32.3	0.6	32.3	0.0	1.8
1940-41	57.8	0.6	46.6	0.1	11.2
1941-42	19.5	0.0	16.4	0.0	1.8
1942-43	53.5	0.2	45.2	0.1	10.7
1943-44	40.5	0.4	32.7	0.0	6.2
1944-45	35.5	0.1	29.7	0.0	4.3
1945-46	30.0	0.1	26.1	0.0	3.0
Average	37.5	0.4	32.5	0.1	5.9

[a] Vegetation on plots accidentally burned over.

Consequently, an effort has been made, by means of hydrographs, to segregate the flow not only as to direct and ground-water runoff but into associated types of ground-water runoff. This analysis, being largely statistical, leaves much for future accomplishment. For the purposes of this investigation the basin runoff has been segregated into the following runoff types: (1) direct runoff; (2) ground-water runoff, (a) storm, (b) seasonal, and (c) perennial.

Although segregation of this basin runoff into these types of runoff may be more or less hypothetical, it aids in a better understanding of the very complex hydrology of these mountains.

Perennial ground-water runoff--Of the three suggested types of mountain ground-water runoff, none is quite so important to the water users as the sustained seepage from the major ground-water bodies. Records of runoff spanning more than a 50-year period indicate that many of these mountain streams have never been known to dry up, even during sustained periods of sub-normal precipitation. This sustained-type ground-water runoff has been designated perennial ground-water runoff.

Figure 1 contains a hydrograph showing the daily discharge of Mill Creek for the period of March 1, 1921, to September, 1926. In addition, the beginning and the end of each period of winter precipitation and summer droughts are also designated on the hydrograph. Some indication of probable snow on the ground is shown by the Squirrel Inn record plotted immediately above the hydrograph.

Experience tends to show that hydrographs plotted on a semilogarithmic projection are often the most productive of analysis, as suggested by BARNES [1939]. In preparing this hydrograph, the long time period available makes it possible to show a wet year followed by three dry years. The wet year of this period was that of 1921-1922 which contained an unusually wet December followed by the somewhat less wet January and February. During these wet periods large quantities of moisture enter the mantle rock as ground-water recharge. In fact, the very much greater runoff at the end of the summer-drought period in 1922 as compared to that of 1921 is conclusive evidence of such a recharge. Beginning in the late spring of 1922 a straight-line recession curve has been developed on this hydrograph largely controlled by the flow at the end of the subsequent summer drought periods. This recession curve is assumed to represent that portion of the runoff from the perennial ground-water storage.

Where this recession is a straight line on a semilogarithmic projection, the following well-known formulas may be used

$$Q = Q_o k^t$$

and

$$R = Qdt$$

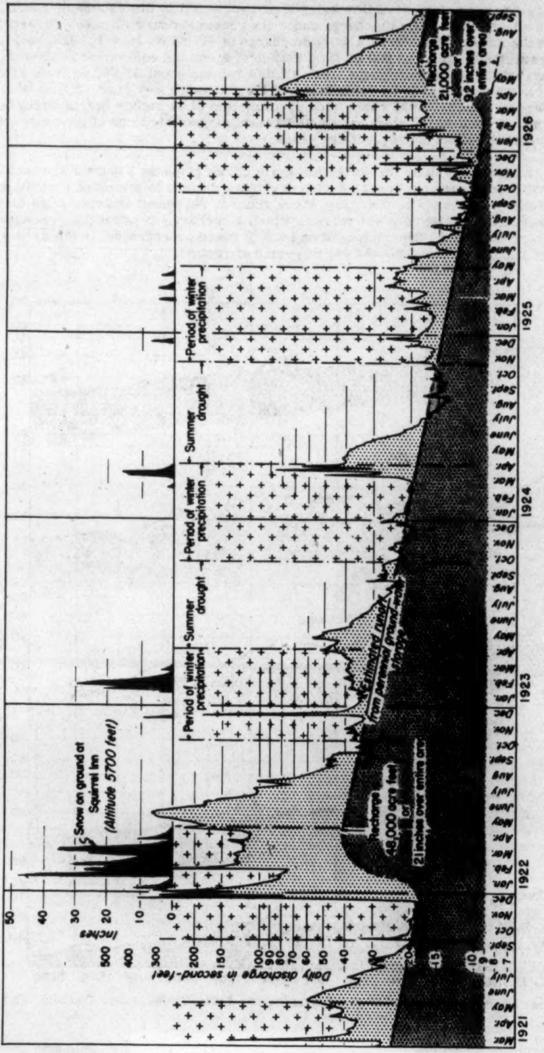

Fig. 1--Hydrograph of daily discharge for Mill Creek where Q_0 is the initial discharge, Q is the discharge after the time interval t in months, k is the depletion factor for the element of flow being analyzed, and R is the volume of runoff. From these formulas the accumulated daily discharge under the recession curve can be converted into storage volumes. In the case of Mill Creek a daily discharge of 40 cfs on June 1, 1922, indicates a perennial ground-water storage of 73,000 ac ft on that date, a volume equivalent to about 2.4 times the average annual runoff of this drainage area. Of this volume about 48,000 ac ft or 21 inches over the entire area was believed to be contributed by the preceding wet year. If this be true, then about one-third of the 1921-1922 basin-wide precipitation of 64 inches in this basin became recharge to the perennial ground-water storage, which, in turn, represented one of the principal sources of the runoff during the three subsequent dry years.

The hydrographs of daily discharge for Lytle Creek given on Figure 2 are included as further indication that these recession curves during dry years do tend to approach a straight-line on a semilogarithmic projection. In each case, these records represent the discharge distribution in dry years preceded by relatively wet years in which a recharge to perennial ground-water storage is known to have occurred. Superimposed on each of these hydrographs is the average perennial ground-water recession curve for the entire period of record.

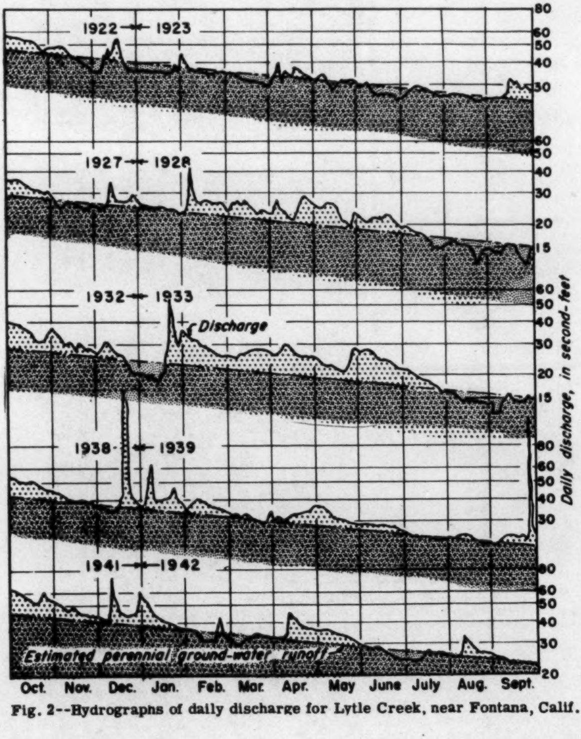

Fig. 2--Hydrographs of daily discharge for Lytle Creek, near Fontana, Calif.

Table 3--Characteristics of the perennial ground-water storage and runoff in the mountain area

Physiographic classification and drainage area	Area	Monthly recession constant k	Estimated maximum storage	Estimated minimum storage	Range in storage	Storage ratio[a]
	sq mi		ac ft/sq mi	ac ft/sq mi	ac ft/sq mi	
Upper mountain areas						
Mill Creek	42.9	0.968	1710	380	1330	1.85
Lytle Creek	47.9	0.943	1210	110	1100	1.75
San Antonio Creek	16.9	0.941	1330	150	1180	1.17
Upper frontal mountain areas						
Cucamonga Creek	10.1	0.944	870	120	750	1.19
Day Creek	4.8	0.932	1850	110	1740	1.87
Lower frontal mountain areas						
City Creek	19.8	0.970	650	170	480	1.16
Strawberry Creek	8.6	0.958	660	120	540	1.20
Waterman Canyon Creek	4.55	0.969	910	160	750	1.60
Mojave River basin						
Deep Creek below Green Valley Creek	15.8	0.972	620	120	500	0.49
Crab Creek	3.92	0.942	300	23	277	0.43
Little Bear Creek	6.62	0.944	510	36	474	. . .
Deep Creek near Hesperia	137	0.952	190	27	163	0.43
Grass Valley Creek	2.75	0.963	370	77	293	. . .

[a] Ratio of range in storage to mean annual runoff.

The drainage areas have been segregated as to their physiographic characteristics in Table 3 and a few of the more pertinent features of this perennial type ground-water storage in the mountain area given. Among the features listed are the estimated maximum and minimum storage in acre feet per square mile for the period of record. The difference between these two items represents the range in storage or that portion of the storage utilized. In the case of Mill Creek in the upper mountain areas, this range in storage amounts to 1330 ac ft per square mile or about 25 inches of water over the entire area. This substantial quantity of water is equivalent to 1.85 times the mean annual runoff. In contrast the runoff records obtained in Deep Creek below Green Valley Creek drainage area in the Mojave River basin suggest a range in perennial ground-water storage of 500 ac ft/sq mi or 9.4 inches over the area. The influence of this storage on the runoff distribution of Deep Creek is very much less pronounced in that the range in usable storage amounts to but 0.49 of its average annual runoff.

Table 3 also contains the recession constant k. This constant is believed to be an important basin characteristic in that the slope of the recession curve is a function of the hydraulic properties of the aquifers in the discharge area and should be closely associated with the physiography and geology of the area. However, the considerable variation in slope of these recession curves indicates that there is little correlation with the physiographic classifications used in preparing this table.

The drainage area of Deep Creek below Green Valley Creek with a recession constant of 0.972 represents the flattest recession slope. With this recessional slope, 50 pct of the perennial ground-water recharge will drain out of the basin in about two years and 80 pct in about 4.5 years. In contrast, a recession constant of 0.932 in the upper frontal mountain drainage area of Day Creek is representative of the steepest recession slope. In this instance, 50 pct of the perennial recharge will drain out of the basin in about 0.8 year, with 80 pct draining out in about 1.9 years.

Seasonal ground-water runoff--The runoff records indicate that the perennial ground-water storage is not recharged every year. However, portions of this complex system of mountain ground-water bodies are recharged each year, except possibly during the very driest of years. Again referring to Figure 1, it will be noted that during each year the runoff in Mill Creek increases in discharge during the period of winter precipitation to a maximum in April or May. From this date until almost the end of the summer-drought period there was a more or less smooth decline in discharge, however, at a very much steeper recessional slope than indicated for the perennial ground-water runoff. This steeper recessional slope suggests seepage through a more permeable discharge area than that containing the perennial ground-water storage. That portion of the runoff in excess of the perennial ground-water runoff and having the characteristics of this more rapid drainage has been designated seasonal ground-water runoff.

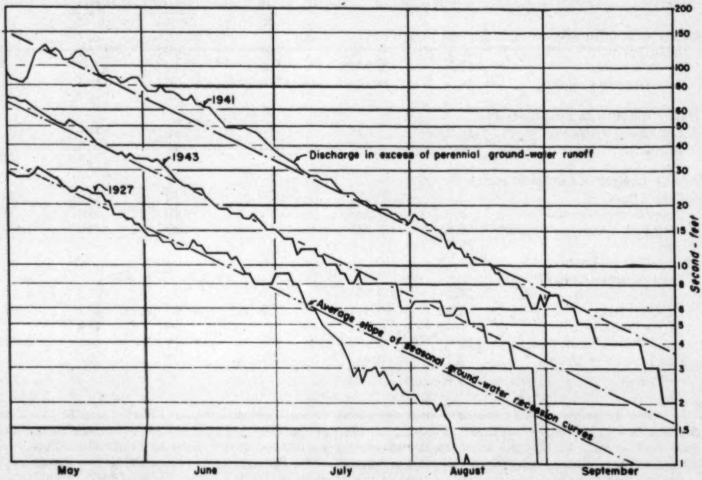

Fig. 3--Hydrographs of daily discharge in San Antonio Creek for the period May to September

Three hydrographs of the daily discharge in excess of the perennial ground-water runoff are given in Figure 3 for the recession period of May to September in the San Antonio Creek drainage area. These records of 1927, 1941, and 1943 show progressively greater daily discharge at the beginning of the recession period without substantial change in slope of the hydrograph. In some instances there may be a small amount of direct runoff from melting snow or rain in the upper areas until about the middle of May, but after that date all the stream flow is believed to be of ground-water origin. The average slope of the seasonal ground-water recession based on the period of record and assumed to be a straight line on this type of projection is superimposed on these hydrographs to show the estimated recession. In general, there is fairly good agreement between the slope of the observational recession and the average seasonal ground-water recessional slope. Assuming this slope to be a straight line, then the San Antonio Creek drainage area would have a maximum observed seasonal ground-water storage of 433 ac ft/sq mi or about 8.1 inches of water over the entire drainage area. Similarly, the maximum seasonal ground-water storage during the period of record, the ratio of this storage to the average annual runoff, and the recession constant k are given in Table 4 for all other mountain drainage areas.

It is evident from Table 4 that although the seasonal ground-water runoff has less significance than the perennial type, its recharge is much more frequent. The maximum observed seasonal ground-water storage ranges from as little as 11 pct of the average annual runoff in Cajon Creek to as much as 61 percent of the average annual runoff in Mill Creek.

As already indicated, the recession slope of the seasonal ground-water runoff is very much steeper than that for the perennial type of ground-water runoff, with these slopes being flattest in the upper frontal mountain areas and steepest in the Mojave River basin. Individually, however, Lone Pine and Lytle Creeks have the flattest recession with a constant of 0.550, which would indicate that 50 pct of the recharge would drain in about 1.2 months and 80 pct in about 2.7 months. In the

Table 4--Characteristics of seasonal ground-water storage and runoff for the mountain area

Physiographic classification and drainage area	Recession constant k	Estimated maximum storage	Storage ratio[a]
		$\frac{\text{ac ft}}{\text{sq mi}}$	
Upper mountain areas			
Mill Creek	0.465	438	0.61
Lytle Creek	0.550	212	0.34
San Antonio	0.481	433	0.43
Upper frontal mountain areas			
Cucamonga Creek	0.542	125	0.20
Day Creek	0.525	202	0.22
Lower mountain areas			
Lone Pine Creek	0.550	20.2	0.24
Cajon Creek	0.500	20.0	0.11
Lower frontal mountain areas			
City Creek	0.446	24.4	0.18
Strawberry Creek	0.422	68.2	0.15
Waterman Canyon Creek	0.472	143	0.31
Mojave River basin			
Deep Creek below Green Valley Creek	0.270	146	0.14
Crab Creek	0.301	152	0.24
Deep Creek near Hesperia	0.374	117	0.31
West Fork Mojave River	0.302	71.8	0.17

[a] Ratio of maximum storage to mean annual runoff.

Deep Creek below Green Valley Creek drainage area, 50 pct of the recharge will drain in 0.5 month and 80 pct in about 1.2 months owing to the constant of 0.270.

An additional characteristic of considerable importance is the time lag between the season's precipitation and the appearance of the seasonal ground-water runoff in the stream channel. Lag, as here defined, represents the time interval between the center of masses of the winter precipitation and identifiable seasonal ground-water runoff. In the case of San Antonio Creek this lag amounted to 2.3 months in 1927, 2.0 months in 1941, and 3.2 months in 1943, these being the three years in which the recession curves are shown on Figure 3. In other mountain areas this lag is often very much longer.

Storm ground-water runoff--A substantial portion of the flood runoff in the Fern Canyon drainage areas reached the stream channels as subsurface flow within or immediately subsequent to the storm period as indicated in Table 1. An underground movement of this rapidity requires not only a highly absorptive mantle rock, but one that is also highly permeable and with a relatively low retention. The occurrence of this type of runoff is clearly indicated on Figure 1 during the storm periods from December, 1921, to February, 1922. In a small rugged drainage area such as Mill Creek, direct runoff under the influence of excessive rates of precipitation should cease within less than 24 hours after the conclusion of this precipitation, yet the storm runoff recession continued for days and often weeks after this period.

The entire concept of storm ground-water runoff and its segregation from other types of runoff is based largely on the shape of the recession curves. Hydrographs of daily discharge for three storm periods in the San Antonio Creek drainage area are plotted on a semilogarithmic projection in Figure 4.

In the selection of these three flood events considerable care was exercised in order that they be among the largest in the period of record and that they occur sufficiently early in the season to insure that no substantial recharge to perennial and seasonal ground-water storage had taken place. The diagram also shows the beginning and ending of each period of precipitation as well as

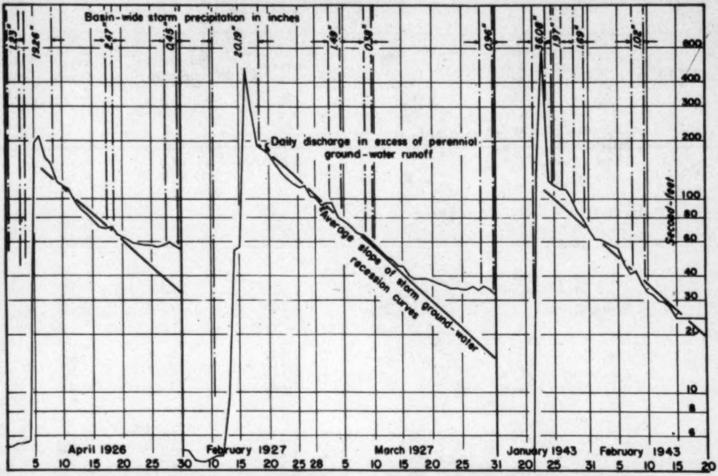

Fig. 4--Hydrographs of daily discharge in San Antonio Creek for selected storm periods

its basin-wide magnitude. As in the case of Mill Creek, it is doubtful if direct runoff occurred for longer than 24 hours after the conclusion of the excessive rates of precipitation in this relatively small, steep drainage area.

The first hydrograph on Figure 4 represents the runoff from the major storm April 4-8, 1926. A daily discharge of slightly more than five cubic feet per second in excess of the perennial ground-water runoff occurring prior to this storm increased to about 210 cfs on April 6, and then decreased to slightly more than 120 cfs by April 9. Because the precipitation had ceased at least 12 hours earlier, it is doubtful if any of the 120 cfs discharge on April 9 represents direct runoff. From April 9 the hydrograph indicates an orderly recession of considerable steepness that tends to follow a straight line on a semilogarithmic projection for the next 10 days. The second hydrograph on Figure 4 is for the storm of February 11-18, 1927, during which the basin-wide precipitation amounted to 20.19 inches. The third hydrograph represents the runoff from the storm of 36.08 inches occurring on January 22-23, 1943. Superimposed on each of these hydrographs is a straight-line recession curve having the average slope obtained from the period of record. In general, there is fair to good agreement between the observational data and the average curve. However, recession slope is very much steeper than for either the seasonal and perennial types of ground-water runoff. This may suggest a more permeable discharge area as well as a more temporary type of storage than either of the two previous types of ground-water runoff.

The main characteristics of the storm ground-water storage and runoff are given in Table 5. In the case of the upper mountain drainage area of Mill Creek the estimated maximum observed storage amounts to 329 ac ft/sq mi or about 6.2 inches and is equivalent to 0.46 of the average annual runoff. However, 50 pct of the ground-water recharge would return to the stream in about 11 days and 90 pct in about 36 days, due to the recession constant k of 0.144.

In the other physiographic groups the observed storage is less and the recession curve even steeper. In the Mojave River basin drainage area of Deep Creek below Green Valley Creek the maximum observed storage amounts to 225 ac ft/sq mi or about 4.2 inches over the drainage area. Having a recession constant k of 0.035, about 50 pct of the storm ground-water recharge would drain into the stream channels in seven days and 90 pct in about 21 days.

Table 5--Characteristics of storm ground-water storage and runoff in the mountain area

Physiographic classification and drainage area	Recession constant k	Estimated maximum storage	Storage ratio[a]
		ac ft/sq mi	
Upper mountain areas			
Mill Creek	0.144	329	0.46
Lytle Creek	0.125	442	0.70
San Antonio Creek	0.151	503	0.50
Upper frontal mountain areas			
Cucamonga Creek	0.088	351	0.56
Day Creek	0.061	266	0.29
Lower mountain areas			
Lone Pine Creek	0.060	10.0	0.12
Cajon Creek	0.041	46.4	0.25
Lower frontal mountain areas			
City Creek	0.020	99.8	0.24
Strawberry Creek	0.056	163	0.36
Waterman Canyon Creek	0.058	220	0.47
Mojave River basin			
Deep Creek below Green Valley Creek	0.035	225	0.22
Crab Creek	0.054	98.8	0.15
Deep Creek near Hesperia	0.061	140	0.37
West Fork Mojave River	0.033	117	0.27

[a] Ratio of maximum storage to mean annual runoff.

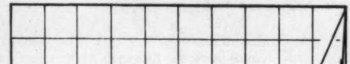

Fig. 5--Relationship between time and runoff

Summary--It is quite evident from the foregoing analysis that a major portion of the runoff in the San Bernardino and Eastern San Gabriel Mountains is subject to complex ground-water influences. In that these influences are controlled largely by the physiography and geology of the region the effect on the runoff distribution will vary considerably from drainage area to drainage area. Probably of most significance, in this respect, is the magnitude of the capacity for ground-water storage. Consequently, a summary of the relationship of the mountain ground-water storage to the mean annual runoff is given in Table 6 as the ratio of storage to runoff observed during the period of record. It is quite evident that ground-water storage of one form or another is greatest in the upper mountain areas and least in the Mojave River basin. It is, therefore, not surprising that the duration curves of daily discharge for certain streams should be completely different even though the mean annual runoff per square mile is almost identical for the areas.

As evidence of this variation in runoff distribution Figure 5 shows graphically the concentration of the average annual precipitation in the mountain area and the average annual runoff for the drainage areas in the upper mountain areas and the Mojave River basin. For the purpose of simplification the average monthly values have been used in preference to daily values in

Table 6--Summary ratios of mountain ground-water storage to mean annual runoff

Physiographic classification and drainage area	Perennial[a]	Seasonal[b]	Storm[c]
Upper mountain areas			
Mill Creek	1.85	0.61	0.46
Lytle Creek	1.75	0.34	0.70
San Antonio Creek	1.17	0.43	0.50
Average	1.59	0.46	0.56
Upper frontal mountain areas			
Cucamonga Creek	1.19	0.20	0.56
Day Creek	1.87	0.22	0.29
Average	1.53	0.21	0.42
Lower mountain areas			
Lone Pine Creek	. . .	0.24	0.12
Cajon Creek	. . .	0.11	0.25
Average	. . .	0.18	0.18
Lower frontal mountain areas			
City Creek	1.16	0.18	0.24
Strawberry Creek	1.20	0.15	0.36
Waterman Canyon Creek	1.60	0.31	0.47
Average	1.32	0.21	0.36
Mojave River basin			
Deep Creek below Green Valley Creek	0.49	0.14	0.22
Crab Creek	0.43	0.24	0.15
Deep Creek near Hesperia	0.43	0.31	0.37
West Fork Mojave River	. . .	0.17	0.27
Average	0.45	0.22	0.25

[a] From Table 3. [b] From Table 4. [c] From Table 5.

developing this diagram. The records show that 50 pct of the mountain precipitation is concentrated in about 2.5 months and that 80 pct occurs in a 4.7-month period. However, the runoff records in the Mojave River basin show an even greater concentration with 50 pct of the runoff occurring in 2.1 months and 80 pct in 4.2 months. In contrast the upper mountain area records show that 50 pct of the runoff occurs over a 3.8-month period and 80 pct over a 7.7-month period. This variation in runoff is not due to altitude or differences in precipitation for these are comparable drainage areas even though in different physiographic groups. This variation in runoff distribution is believed to be largely due to the influence of mountain ground-water storage in close combination with the absorptive and retentive qualities of the mantle rock. This entire analysis should be considered, however, as merely introductory to a more complete examination of the hydrologic properties of the mountain mantle rock.

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EVAPOTRANSPIRATION AND OTHER WATER LOSSES ON SOME ASPEN FOREST TYPES IN RELATION TO WATER AVAILABLE FOR STREAM FLOW

A. R. Croft and L. V. Monninger

Abstract--This paper reports the effects of altering an aspen forest cover in Utah on evapotranspiration losses, overland flow, erosion, and mantle storage deficits during three successive growing seasons. These data, together with supplemental measures of winter precipitation and estimates of evaporation from snow, provided a basis for estimating amounts of water available for stream flow. Removal of aspen trees, leaving the herbaceous understory and litter undisturbed, reduced evapotranspiration losses and increased the amount of water available for stream flow by about four inches without seriously increasing overland flow or soil erosion during summer rains. Removal of the remaining herbaceous cover further reduced evapotranspiration losses and increased the amount of water available to streams by an additional four inches but resulted in an undesirable increase in summer rainfall runoff and soil loss.

Introduction--Most of the water, either stream flow or ground water, used in the semi-arid valleys of the West falls as rain or snow on distant mountains that receive two or three times more precipitation than the valleys. Processes of evaporation from the ground surface and transpiration by plants account for the loss of relatively large quantities of water, some of which might otherwise be available for stream flow. How much of the water thus lost could be made available for stream flow by altering or removing the vegetal cover is therefore of considerable interest in the West. This paper reports some phases of investigation of this problem on aspen-herbaceous sites in northern Utah.

During the period 1936-46, records from surface runoff plots on the headwater slopes of Parrish Canyon near Farmington, Utah, showed that aspen-herbaceous forest cover prevented overland flow and erosion during high-intensity summer rains as well as during spring snow melt [BAILEY, CRADDOCK, and CROFT, 1947]. Intermingled sites with a depleted, weedy plant cover were shown to be inadequate for controlling rainstorm runoff.

In 1947 additional measurements were begun on this same study area to determine total precipitation, consumptive losses, and water available for stream flow under three conditions of plant cover. Measurements of rainstorm runoff and soil erosion were also made to determine the relation of each cover condition to these phenomena.

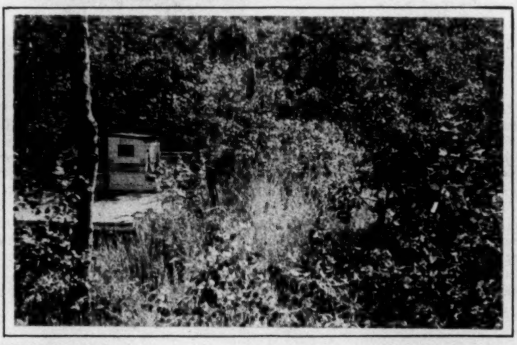

Fig. 1--Natural aspen-herbaceous cover on runoff Plot 10

Methods--Cover consisted of the natural aspen-herbaceous vegetation, herbaceous vegetation after removal of aspen trees, and bare soil (see Fig. 1-3). On the aspen sites there were, on the average, about 3000 trees per acre from one to six inches in diameter. The herbaceous understory of mixed grasses and broadleaf plants had a density of about 41 pct. Litter and duff covered an additional 46 pct of the ground surface, making a total understory ground cover density of 87 pct.

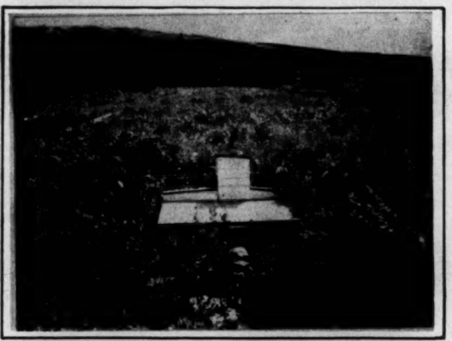

Fig. 2--Herbaceous Plot 8 after removal of aspen trees

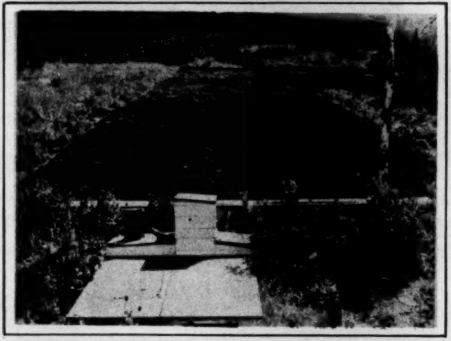

Fig. 3--Bare Plot 7 after removal of vegetation and litter

Estimates of water consumption losses were obtained on nine study plots. Four of these were 1/10-acre runoff plots and five were soil-moisture plots, of which three were 30 × 80 feet and two were 20 × 20 feet. Water losses under normal aspen-herbaceous cover were obtained for three consecutive years on one plot, for two years on another, and for one year on two other plots. Losses from herbaceous cover were obtained for three years on one plot and for one year on two other plots. Losses from bared sites were obtained for three years on one plot and for one year on another (Table 1).

The method of determining water available for stream flow from the three cover conditions consisted essentially of measuring total annual precipitation and water losses due to rainfall interception, evapotranspiration, and evaporation from snow. The difference between precipitation and these consumptive losses was assumed to represent water available for stream flow. The relationship of the hydrologic factors involved is expressed by

$$S = (P_w + P_s) - [I + E + T_1 + T_2] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Table 1--Schedule of evapotranspiration measurements

Study plots		Cover conditions		
Designation	Size	1947	1948	1949
	ac			
Soil moisture 10-A	0.05	Aspen	Aspen	Aspen
Soil moisture 8-A	0.05	Herbaceous	Herbaceous	Herbaceous
Soil moisture 7-A	0.05	Bare	Bare	Bare
Soil moisture C	0.01	....	Aspen	Aspen
Soil moisture D	0.01	....	Aspen	Herbaceous
Runoff 10	0.10	....	....	Aspen
Runoff 9	0.10	....	....	Aspen
Runoff 8	0.10	....	....	Herbaceous
Runoff 7	0.10	....	....	Bare

in which S = water available for stream flow, P_w = winter precipitation, P_s = summer precipitation, I = interception, E = evaporation from snow, T_1 = summer evapotranspiration, and T_2 = winter transpiration.

Precipitation--The mean annual precipitation was 52.77 inches, of which 7.34 inches fell during the summer growing season, June-September, with the remainder, 45.43 inches, falling as rain and snow during the winter season, October-May (see Table 2). Summer precipitation varied from 3.86 inches in 1949 to 9.75 inches in 1948. The greatest winter precipitation was 47.10 inches in 1948-49 and the lowest was 44.18 in 1946-47.

Table 2--Winter precipitation (October-May) and summer precipitation at the ground surface by cover condition (June-September)

Year	Winter precipitation[a]	Bare		Herbaceous		Aspen-herbaceous	
		Summer precipitation	Total	Summer precipitation	Total	Summer precipitation	Total
	inch	inch	inch	inch	inch	inch	inch
1946-47	44.18	8.42	52.60	7.35	51.53	6.58	50.76
1947-48	45.00	9.75	54.75	8.75	53.75	8.47	53.47
1948-49	47.10	3.86	50.96	3.61	50.71	3.51	50.61
Mean annual	45.43	7.34	52.77	6.57	52.00	6.19	51.62

[a] Corrected for calculated evaporation from snow pack.

Winter precipitation was measured at only one location on the study area, using snow course and storage-type rain and snow gages. Summer precipitation was measured on the plots with trough rain gages (six per 1/10-acre) set on the ground. These measured the precipitation reaching the ground so that no correction for interception by the leafy herbaceous and aspen vegetation was necessary in determining total net precipitation at the ground surface.

Water losses

Precipitation losses resulted from interception of rain by vegetation, transpiration by plants, and evaporation from the ground surface during the growing season, and transpiration by trees and evaporation from the snow pack during the winter. Precipitation not consumed or dissipated by these processes was considered to have passed through the soil mantle and thus to have become available for stream flow. In some cases small amounts of water ran off as overland flow.

Interception--Interception of rainfall by vegetation accounted for only minor losses of water. Mean growing-season interception was 1.16 inches (15.8 pct) for the aspen-herbaceous type, and 0.77 inch (10.5 pct) for the herbaceous type (Table 3). These values are calculated by subtracting the net catch at the ground surface for each vegetal type from the total catch on the bare type. Winter interception was negligible because herbaceous plants were soon buried beneath the snow and the smooth-barked, leafless aspen trees intercepted only small amounts of snow.

Evaporation from snow--Since no snow evaporation data were taken during 1947-49, it was necessary to utilize data from various studies made on similar sites. CROFT [1944] at the

Table 3--Interception by aspen-herbaceous and herbaceous vegetal types

Year	Bare		Herbaceous		Aspen-herbaceous	
	Rainfall	Inter-ception	Rainfall	Inter-ception[a]	Rainfall	Inter-ception[b]
	inch	inch	inch	inch	inch	inch
1947	8.42	. . .	7.35	1.07	6.58	1.84
1948	9.75	. . .	8.75	1.00	8.47	1.28
1949	3.86	. . .	3.61	0.25	3.51	0.35
Mean seasonal	7.34	. . .	6.57	0.77	6.19	1.16

[a] Bare minus herbaceous.

[b] Bare minus aspen.

Great Basin Branch Experiment Station on the Wasatch Plateau, Utah, at 8800-ft elevation, found evaporation from snow between April 28 and May 21, 1942, to be 0.26 inch or an average daily loss of about 0.011 inch. Applying this average value to a 210-day snow period, an evaporation loss of 2.31 inches is suggested.

At this same site BAKER [1917] measured mean daily evaporation of 0.0175 inch, or a total of 3.15 inches during a 180-day snow period. The extent to which condensation may have offset the evaporation obtained in these two studies is not known. At the Fraser Experimental Forest in Colorado, WILM and DUNFORD [1948] found evaporation to be 2.23 inches during the period of snow cover. The method used by these investigators evaluated the condensation factor.

From the Utah data, snow evaporation values were placed at 3.00 inches for the bare type, 2.75 inches for the herbaceous type, and 2.50 inches for the aspen type. These differences include estimates of the effect of vegetation in reducing evaporation as suggested by the Utah [BAILEY, CRADDOCK, and CROFT, 1947] studies.

Rainstorm runoff--Losses of water from the plots by overland flow from summer rains were negligible except from the bare type (Table 4). Average annual surface runoff was about 0.01 inch (0.16 pct) from 6.19 inches of rain on the aspen type, and 0.02 inch (0.30 pct) from 6.57 inches of rain on the herbaceous type. Runoff from 7.34 inches of rain on the bare type was 0.40 inch (5.45 pct). All snow melt infiltrated into the soil.

Table 4--Surface runoff from summer rains and infiltration on three cover types

Year	Bare			Herbaceous			Aspen-herbaceous		
	Precipi-tation	Run-off	Infil-tration	Precipi-tation	Run-off	Infil-tration	Precipi-tation	Run-off	Infil-tration
	inch	inch	inch	inch	inch	inch	inch	inch	inch
1947	8.42	0.32	8.10	7.35	0.01	7.34	6.58	0.01	6.57
1948	9.75	0.68	9.07	8.75	0.06	8.69	8.47	0.03	8.44
1949	3.86	0.19	3.67	3.61	0	3.61	3.51	0	3.51
Mean annual	7.34	0.40	6.94	6.57	0.02	6.55	6.19	0.01	6.18

Summer evapotranspiration--The seasonal soil-moisture deficit (field capacity minus depletion-moisture content) plus water added to the soil by summer rains was considered to represent summer evapotranspiration losses. Water entering the ground from rains during the growing season is considered in this category because in this region most rains are so small they wet the soil only a few inches and the water is soon lost by evaporation or transpiration. These minor rains, therefore, have practically no immediate effect on water yield, but sometimes they do tend to raise the moisture content of the soil. By so doing they decrease the seasonal soil-moisture deficit. This affects stream flow because less water is required to produce seepage flow to streams the following year.

The factors involved in determining summer evapotranspiration are expressed by

$$L = (W_1 - W_2) + (P - R) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

in which L = evapotranspiration loss, W_1 = field-moisture capacity of a six-foot deep mantle, W_2 = depletion-moisture content on the six-foot mantle, P = summer rainfall at the ground surface, and R = surface runoff from rains.

Field capacity--Field capacity was determined by foot-depth horizons to a depth of six feet on all sites by both field and laboratory methods. The field method consisted of obtaining soil-moisture percentage measurements from soil samples taken with a geotome (a long soil-sampling tube) immediately after the disappearance of snow and again after late spring rains. These samples were obtained on six different occasions on each of the nine plots; twice in 1947, three times in 1948, and once in 1949. The six values for each plot were averaged to obtain field capacity. The same soil samples were composited by foot-depths for a laboratory determination of percentage moisture at 1/3 atmosphere pressure in accordance with the method described by COLMAN [1947] for determination of field-moisture capacity.

Apparent density of soil was also determined for each foot-depth from volume-weight samples taken from pits adjoining the several plots and from the soil-moisture samples composited by foot-depths. These values are given in Table 5.

Table 5--Apparent density of soil from evapotranspiration study plots

Plot type and designation	0-12 inch depth	12-24 inch depth	24-36 inch depth	36-48 inch depth	48-60 inch depth	60-72 inch depth
Aspen						
10	1.15	1.42	1.53	1.55	1.55	1.55
10-A	1.14	1.44	1.57	1.60	1.61	1.62
9	1.14	1.33	1.45	1.52	1.54	1.54
C	1.01	1.19	1.38	1.48	1.52	1.53
D	1.06	1.22	1.40	1.50	1.51	1.50
Herbaceous						
8	1.03	1.14	1.24	1.45	1.57	1.61
8-A	1.05	1.18	1.32	1.44	1.52	1.57
D	1.06	1.22	1.40	1.50	1.51	1.50
Bare						
7	1.02	1.11	1.23	1.44	1.50	1.52
7-A	1.08	1.22	1.35	1.46	1.52	1.54

The moisture percentages obtained from the field samples and the laboratory tests were converted to inches of water per foot of mantle depth by

$$\text{Water (inches)} = \text{percent moisture} \times \text{apparent density} \times 12/100$$

The field-capacity values of the soil as determined by the field method averaged about 3.50 inches per foot of depth in the 0- to 12-inch horizon and about 3.00 inches in the 60- to 72-inch horizon (Table 6, FMC). The field capacity for the total six-foot depth was lowest on the aspen plots with a range from 16.19 to 19.07 inches. The herbaceous plots had intermediate field capacities, ranging between 18.03 and 20.54 inches. The bare plots had the highest water-holding capacities with a range from 20.56 to 20.59 inches. Slightly lower but statistically non-significant values were obtained from the 1/3 atmosphere determinations.

Depletion-moisture content--The depletion-moisture content of the six-foot deep mantles on each plot was obtained from soil samples taken at the end of the growing season (Table 6, DMC). These same samples were tested for water content under 15 atmospheric pressures as described by RICHARDS and WEAVER [1944] for determining the lower limit of water available to plants. The 15-atmosphere values in Table 6 are believed to be approximate wilting percentages and are referred to as such herein.

For all aspen plots the depletion-moisture storage in the six-foot deep mantle was slightly higher than the calculated wilting percentage, indicating that this type used practically all available water to a depth of six feet (Table 6, DMC). On the herbaceous plots the depletion-moisture content of the six-foot deep mantle was from about three to six inches higher than the water content indicated by the wilting percentage with most of the unused water in the lower three feet of the mantle. On the bare plots from eight to 11 inches of water above the wilting percentage remained in the six-foot soil mantle at the end of the growing season.

Soil-moisture deficit--Soil-moisture deficit is the difference between soil water content at field capacity and at depletion content. Deficits for each foot of depth of mantle on each of the nine sites as given in Table 6, SMD are the differences between field-capacity values FMC and depletion-moisture values DMC in Table 6.

Table 6--Field-moisture capacity, depletion-moisture content, and soil-moisture deficit, together with laboratory determination of soil under pressure of 15 atmospheres and 1/3 atmosphere

Plot type and designation	Purpose of measurement	Type of measurement	Water content of soil at various depths calculated to depth-inches						
			0-12 inches	12-24 inches	24-36 inches	36-48 inches	48-60 inches	60-72 inches	0-72 inches
Aspen 10	FMC[a]	Field	3.46	3.19	2.83	2.59	2.64	2.92	17.63
		1/3 at.	2.79	3.37	3.05	2.85	2.60	2.36	17.02
	DMC[b]	1949	0.81	0.87	0.80	0.73	0.86	0.96	5.03
		15 at.	0.91	0.99	0.82	0.84	0.70	0.66	4.92
	SMD[c]	1949	2.65	2.32	2.03	1.86	1.78	1.96	12.60
Aspen 10-A	FMC	Field	3.46	2.97	2.54	2.24	2.37	2.61	16.19
		1/3 at.	2.82	2.82	2.55	2.30	2.32	2.46	15.27
	DMC	1947	1.08	1.04	0.86	0.70	0.61	0.72	5.01
		1948	0.93	0.85	0.86	0.67	0.79	1.51	5.61
		1949	0.88	0.94	0.97	0.78	0.73	0.84	5.14
		15 at.	1.12	0.94	0.71	0.62	0.61	0.70	4.70
	SMD	1947	2.38	1.93	1.68	1.54	1.76	1.89	11.18
		1948	2.53	2.12	1.68	1.57	1.58	1.10	10.58
		1949	2.58	2.03	1.57	1.46	1.64	1.77	11.05
Aspen 9	FMC	Field	3.46	3.41	3.11	2.93	2.92	3.24	19.07
		1/3 at.	3.43	3.46	3.33	2.89	2.36	2.29	17.76
	DMC	1949	1.01	1.30	1.14	1.12	0.90	0.84	6.31
		15 at.	1.18	1.19	1.01	0.92	0.70	0.69	5.69
	SMD	1949	2.45	2.11	1.97	1.81	2.02	2.40	12.76
Aspen C	FMC	Field	3.81	3.18	2.82	2.91	3.14	3.17	19.03
		1/3 at.	2.86	3.00	2.97	3.00	3.19	3.27	18.29
	DMC	1948	1.11	1.04	0.87	1.22	1.57	1.86	7.67
		1949	0.89	1.03	0.97	1.04	1.06	1.34	6.33
		15 at.	1.27	0.96	0.82	0.90	1.10	1.20	6.25
	SMD	1948	2.70	2.14	1.95	1.69	1.57	1.31	11.36
		1949	2.92	2.15	1.85	1.87	2.08	1.83	12.70
Aspen D	FMC	Field	3.65	3.47	3.04	2.69	2.75	2.43	18.03
		1/3 at.	2.89	3.13	3.15	3.10	3.39	2.88	18.54
	DMC	1948	1.24	1.15	0.88	0.98	1.13	1.26	6.64
		15 at.	1.02	1.00	0.88	0.87	1.09	0.88	5.74
	SMD	1948	2.41	2.32	2.16	1.71	1.62	1.17	11.39
Herbaceous 8	FMC	Field	3.39	3.58	3.53	3.41	3.26	3.37	20.54
		1/3 at.	2.91	3.17	2.92	2.86	3.24	3.99	19.09
	DMC	1949	0.87	1.14	1.20	2.30	3.00	3.94	12.45
		15 at.	0.97	1.16	1.28	1.29	1.35	1.78	7.83
	SMD	1949	2.52	2.44	2.33	1.11	0.26	-0.57	8.09
Herbaceous 8-A	FMC	Field	3.46	3.63	3.40	3.28	3.19	3.55	20.51
		1/3 at.	3.33	3.37	3.46	3.02	3.49	3.75	20.42
	DMC	1947	1.18	1.33	1.68	2.68	3.49	3.14	13.50
		1948	1.18	1.45	1.25	1.69	2.82	2.73	11.12
		1949	0.94	1.25	1.44	2.02	3.33	3.88	12.86
		15 at.	1.18	1.32	1.16	1.29	1.38	1.54	7.87
	SMD	1947	2.28	2.30	1.72	0.60	-0.30	0.41	7.01
		1948	2.28	2.18	2.15	1.59	0.37	0.82	9.39
		1949	2.52	2.38	1.96	1.26	-0.14	-0.33	7.65
Herbaceous D	FMC	Field	3.65	3.47	3.04	2.69	2.75	2.43	18.03
		1/3 at	2.89	3.13	3.15	3.10	3.39	2.88	18.54
	DMC	1949	0.85	1.00	1.12	1.26	1.84	2.38	8.45
		15 at.	1.02	1.00	0.88	0.87	1.09	0.88	5.74
	SMD	1949	2.80	2.47	1.92	1.43	0.91	0.05	9.58

(Continued)

Table 6--Field-moisture capacity, depletion-moisture content, and soil-moisture deficit, together with laboratory determination of soil under pressure of 15 atmospheres and 1/3 atmosphere (Concluded)

Plot type and designation	Purpose of measurement	Type of measurement	Water content of soil at various depths calculated to depth-inches						
			0-12 inches	12-24 inches	24-36 inches	36-48 inches	48-60 inches	60-72 inches	0-72 inches
Bare 7	FMC	Field	3.33	3.53	3.65	3.53	3.33	3.19	20.56
		1/3 at.	3.10	3.07	2.94	3.02	3.21	2.86	18.20
	DMC	1949	2.42	2.71	2.92	3.48	2.74	3.05	17.32
		15 at.	1.22	1.04	0.95	1.01	1.02	1.06	6.30
	SMD	1949	0.91	0.82	0.73	0.05	0.59	0.14	3.24
Bare 7-A	FMC	Field	3.26	3.48	3.78	3.66	3.40	3.01	20.59
		1/3 at.	3.18	3.58	3.86	3.35	2.97	3.01	19.95
	DMC	1947	2.36	2.78	3.22	3.33	3.08	2.27	17.04
		1948	2.19	2.82	3.02	2.74	2.44	2.64	15.85
		1949	1.96	2.59	2.90	2.48	2.44	2.46	14.83
		15 at.	1.03	1.22	1.27	1.13	0.95	0.98	6.58
	SMD	1947	0.90	0.70	0.56	0.33	0.32	0.74	3.55
		1948	1.07	0.66	0.76	0.92	0.96	0.37	4.74
		1949	1.30	0.89	0.88	1.18	0.96	0.55	5.76

[a]Field-moisture capacity. [b]Depletion-moisture content. [c]Soil-moisture deficit

Plots of the aspen type had the largest soil-moisture deficits with values from 10.58 to 12.76 inches of water. Deficits on herbaceous plots were about 3.5 inches less, with values from 7.01 to 9.58 inches. Deficits on bare plots ranged from 3.24 to 5.76 inches. These were about seven inches lower than on aspen plots.

Effect of root depth--These soil-moisture-deficit differences are closely associated with root depth. For example, aspen roots occupied the soil mantle to the study depth of six feet, and all available moisture was used to this depth. On the herbaceous type, all available water was used in the root zone from zero to four feet, but very little was removed below the four-foot depth.

Evaporation was less effective than transpiration in removing water from the soil even in the surface foot. Although the soil on the bare type was dried considerably below the wilting percentage to a depth of three inches, only about half the water available to plants was removed from the first foot of soil (Table 7), whereas on the vegetated plots all available moisture was removed from this depth. Only about one-third of the water available to plants was removed from the respective increments of depth from two to six feet. On some of the bare plots, coarse soil below the 36-inch depth prevented collection of adequate samples with the geotome. It may be, therefore, that indicated losses of water below 36 inches are due to sampling error, since it is unlikely that evaporation removed measurable quantities of water from the soil below this depth.

Table 7--Average available water and soil-moisture deficit by foot-depth in soil of the bare type

Depth	Storage		Available water	Soil moisture deficit
	Field capacity	Wilting percentage		
inch	inch	inch	inch	inch
0-12	3.30	1.12	2.18	1.04
12-24	3.50	1.13	2.37	0.77
24-36	3.72	1.11	2.61	0.73
36-48	3.60	1.07	2.53	0.62
48-60	3.36	0.98	2.38	0.71
60-72	3.10	1.02	2.08	0.45

Rates of moisture depletion--The march of moisture in the six-foot deep mantles of the three types varied considerably during the growing season as shown by data for 1949 (Fig. 4). On the bare type the maximum soil-moisture deficit of 4.5 inches was reached by about August 15, indicating an average daily water loss of 0.06 inch for 75 days. The 8.4-inch deficit in the mantle of

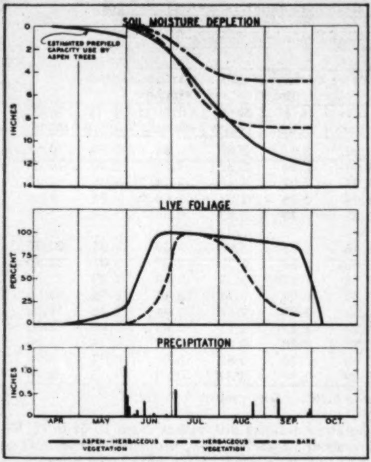

Fig. 4--Soil-moisture depletion in relation to live foliage and precipitation, 1949

the shallow-rooted herbaceous type was reached about the same time, indicating an average daily loss of about 0.112 inch for 75 days. The six-foot deep mantle of the aspen type lost water throughout the entire 120-day growing season creating a soil-moisture deficit of 12.3 inches. The average daily loss was 0.101 inch.

Aspen foliage remained green until killed by frost about October 1, presumably because its deep root system was always in contact with available water. Foliage of the herbaceous type began to dry up about August 1, no doubt because most of the available water in reach of its shallow root system had been used by that time.

The live foliage and soil-moisture-deficit data for the herbaceous type provide a means of postulating the effect of thinning this type on water consumption (Fig. 4). There were at least 30 days of growing weather left after the maximum seasonal soil-moisture deficit was reached about August 15. Had the herbaceous type been thinned considerably, the remaining plants would probably have stayed green longer, and much, if not all, of the water available to the roots would have been used by the end of the growing season. Then, too, thinning would have permitted invasion of water-consuming annuals, some of which have root systems as deep as grasses.

Winter transpiration--An estimate was made of the amount of water consumed by aspen during flowering and leaf development in April and May while snow was melting and seepage water was passing through the soil. Average leaf development (including catkins which began to break open about April 1) in this period was about one-fifth of that in June at which time the daily use of water by aspen was 0.08 inch. Assuming water loss to be roughly proportionate to leaf development, the use of water by aspen during the 60-day prefield capacity period was calculated to be about one inch (60 × 0.08/5). Since the herbaceous plants did not begin growth until after the snow had melted and the soil reached field capacity, all losses from this type are accounted for in the seasonal soil-moisture deficit plus summer rains.

Total evapotranspiration losses--Summer and winter evapotranspiration losses are summarized in Table 8. Summer losses include seasonal soil-moisture deficit plus moisture added to the soil from summer rains. Winter losses include only estimated transpiration from aspen during snow melting. The total average seasonal evapotranspiration losses were 18.70 inches from the aspen types, 14.83 inches from the herbaceous types, and 11.21 inches from the bare types.

The 18.70-inch water loss by the aspen type includes 1.0 inch of prefield capacity use, 6.18 inches of summer rainfall, and a soil-moisture deficit of 11.52 inches of water. This high deficit resulted from removal of practically all water available in the zone occupied by plant roots which in this type included the entire six-foot deep soil mantle. The total seasonal losses varied from 16.79 inches in 1949 to 20.55 inches in 1948. This difference is due mainly to five inches more summer rainfall in 1948 than in 1949.

Since the soil-moisture deficit varied only about one inch from year to year, it exerted only a minor influence on seasonal loss difference.

The 14.83-inch water loss by the herbaceous type includes slightly more summer rainfall than for aspen due to less interception by the herbaceous type, and a smaller soil-moisture ~~deficit~~ deficit--only 8.28 inches. The decrease of 3.24 inches in evapotranspiration is due to the fact that water was removed only to a depth of about four feet, which is the approximate depth of penetration of the herbaceous plant roots. Total seasonal losses varied from 12.05 inches in 1949 to 18.08 inches in 1948. Although the soil-moisture deficit was one inch more in 1948 than in 1949, the seasonal variation resulted mainly from a five-inch difference in summer rainfall.

Table 8--Summer and winter evapotranspiration losses

Type of plot	Year	Summer: Soil-moisture deficit[a]	Summer: Rains[b]	Summer: Total	Winter transpiration[c]	Total annual
		inch	inch	inch	inch	inch
Aspen-herbaceous	1947	11.18	6.57	17.75	1.0	18.75
	1948	11.11	8.44	19.55	1.0	20.55
	1949	12.28	3.51	15.79	1.0	16.79
	Average	11.52	6.18	17.70	1.0	18.70
Herbaceous	1947	7.01	7.34	14.35	0	14.35
	1948	9.39	8.69	18.08	0	18.08
	1949	8.44	3.61	12.05	0	12.05
	Average	8.28	6.55	14.83	0	14.83
Bare	1947	3.55	8.10	11.65	0	11.65
	1948	4.74	9.07	13.81	0	13.81
	1949	4.50	3.67	8.17	0	8.17
	Average	4.26	6.94	11.21	0	11.21

[a] Field capacity minus depletion moisture storage.

[b] Summer rainfall at ground surface minus surface runoff.

[c] Estimated.

The low average seasonal water loss from the bare type of only 11.20 inches is accounted for by the small soil-moisture deficit of 4.26 inches, since rainfall was about the same as on the other two types. Total seasonal loss varied from 8.17 inches in 1949 to 13.81 inches in 1948. This difference in loss is due to different amounts of precipitation each summer that penetrated the surface soil just a few inches only to be lost by evaporation. The soil-moisture deficit in the bare type was due almost exclusively to evaporation since vegetation was clipped or burned at frequent intervals during the growing season.

Water available for stream flow

In Table 9 is presented a summary of all components involved in determining water available for stream flow as expressed in (1). These components are presented in three groups: annual precipitation, water losses from the precipitation, and the residual which is water available for stream flow.

Table 9--Total precipitation, water losses, and water available for stream flow

Factor	Bare 1947	Bare 1948	Bare 1949	Bare Aver	Herbaceous 1947	Herbaceous 1948	Herbaceous 1949	Herbaceous Aver	Aspen-herbaceous 1947	Aspen-herbaceous 1948	Aspen-herbaceous 1949	Aspen-herbaceous Aver
	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch
Precipitation												
Winter	44.18	45.00	47.10	45.43	a	a	a	a	a	a	a	a
Summer	8.42	9.75	3.86	7.34	a	a	a	a	a	a	a	a
Total	52.60	54.75	50.96	52.77	52.60	54.75	50.96	52.77	52.60	54.75	50.96	52.77
Water losses												
Summer interception	0	0	0	0	1.07	1.00	0.25	0.77	1.84	1.28	0.35	1.16
Evaporation from snow	3.00	3.00	3.00	3.00	2.75	2.75	2.75	2.75	2.50	2.50	2.50	2.50
Summer evapotranspiration	11.65	13.81	8.17	11.21	14.35	18.08	12.05	14.83	17.75	19.55	15.79	17.70
Winter evapotranspiration	0	0	0	0	0	0	0	0	1.00	1.00	1.00	1.00
Total	14.65	16.81	11.17	14.21	18.17	21.83	15.05	18.35	23.09	24.33	19.64	22.36
Water available for stream flow												
Overland flow	0.32	0.68	0.19	0.40	0.01	0.06	0	0.02	0.01	0.03	0	0.01
Seepage flow	37.63	37.26	39.60	38.16	34.42	32.86	35.91	34.40	29.50	30.39	31.32	30.40
Total	37.95	37.94	39.79	38.56	34.43	32.92	35.91	34.42	29.51	30.42	31.32	30.41

[a] Gross precipitation was assumed to be the same for all types because they were close together.

On the bare type, average annual precipitation was 52.77 inches from which losses were 14.21 inches, leaving a balance of 38.56 inches of water available for stream flow all of which was seepage flow except for 0.40 inch which left the plots by overland flow. Here about 73 pct of total annual precipitation became available for stream flow but the 0.40 inch of overland flow caused erosion, as will be shown later.

On the herbaceous type, mean annual precipitation was 52.77 inches, and losses were 18.35 inches, leaving 34.42 inches of water available for stream flow, or about 65 pct of the annual precipitation. On the aspen type mean annual precipitation was 52.77 inches, from which losses were 22.36 inches, leaving 30.41 inches of water, or about 58 pct of the annual precipitation, available for stream flow. Since surface runoff was practically nil on both vegetal types, all water available to streams was from seepage flow.

The 4.01 inches of water saved by cutting aspen and the 8.15 inches saved by removing all vegetation represent about eight and 15 pct, respectively, of the total annual precipitation, but they represent about 13 and 27 pct, respectively, of the annual water available for stream flow from the natural aspen sites.

The relationship of the approximate four inches of water saved by cutting aspen and the eight inches saved by cutting both aspen and herbaceous plants to the water available for stream flow varies from year to year. This is due to the fact that water available for stream flow is a residual of the precipitation which varies from year to year, whereas losses have a tendency to remain roughly the same. Thus any precipitation variation is reflected almost wholly in the water available for stream flow. For example, in 1949 when precipitation was 50.96 inches, the 4.59 inches of water saved by cutting aspen was about 15 pct of the water available for stream flow from the natural aspen type, but in a year when precipitation is only about 30 inches a saving of 4.59 inches of water would represent about 44 pct of the water available for stream flow assuming losses to be about the same each year.

Effect of vegetal changes on runoff

Another important aspect of this study is the effect of partial and complete removal of vegetation on rainstorm runoff (overland flow) and soil erosion.

The natural aspen type with its understory of herbaceous plants gives almost complete control of overland flow and erosion. Rainstorm runoff from this type has averaged less than one per cent and no measurable quantities of soil have been eroded during the period 1947-49 (Table 10). Moreover, the effectiveness of aspen-herbaceous cover has been tested by 153 summer rains since 1936, (some with intensities as high as 6.84 in/hr for five minutes) [CROFT and MARSTON, 1950]. Since removal of aspen trees from Plot 8 in June 1947, the remaining herbaceous vegetation has controlled rainstorm runoff and soil erosion almost as effectively as before treatment, although rainfall intensities have not yet been as high as before.

Removal of all vegetation unleashed the extremely high surface runoff and erosion potentials that characterize these mountain lands, as shown by data from Plot 7. Only 0.35 inch of rainfall with intensities as low as 1.20 inches per hour for five minutes resulted in 29 pct runoff and soil loss at the rate of 0.84 ton per acre. The heaviest storm on the study area since treatment began (0.70 inch with intensity of 4.20 in/hr) occurred July 10, 1950. It caused 52 pct runoff as overland flow, and soil was eroded at the rate of 12.5 tons per acre. Watershed conditions that produce such extravagant soil losses cannot be tolerated even though they result in a substantial saving of water. Such depleted areas amounting to less than ten per cent of drainage basin areas have resulted in disastrous rainstorm floods as shown by BAILEY, CRADDOCK, and CROFT [1947].

Discussion

Removal of deep-rooted aspen trees reduced evapotranspiration loss from about 22 inches to about 18 inches, thereby increasing water available for stream flow about four inches. Removal of all vegetation, thus eliminating transpiration, reduced the loss to about 14 inches and increased water available for stream flow by an additional four inches. Since bare ground lost about 14 inches of the water, the actual water cost of the two aspen and herbaceous plant types may be reduced by this amount. Accordingly, the net water cost of the aspen type was only eight inches and that of the herbaceous type only four inches.

Since data in this study were obtained on plots of 1/10 to 1/100 acre in area, and in a zone of high elevation and precipitation, application of results to entire watersheds which contain great

Table 10--Summer rainfall runoff and soil losses under three aspen forest cover conditions

Precipitation[a]			Aspen-herbaceous		Herbaceous		Bare	
Storm dates	Amount	Max. rate	Run-off	Soil loss	Run-off	Soil loss	Run-off	Soil loss
	inch	in/hr	inch	ton/ac	inch	ton/ac	inch	ton/ac
1947								
Aug. 2	0.28	1.80	0	0	T	0	0.04	0.636
Aug. 4	0.26	0.24	0	0	T	0	T	0
Aug. 9-10	0.65	2.76	T	0	T	0	0.23	3.316
Aug. 27	0.34	1.56	0	0	0	0	0.04	0.234
Sep. 17-18	1.18	0.36	T	0	T	0	0.02	0
Total	2.71	...	...	0	...	0	0.33	4.186
1948								
June 20-22	3.90	1.80	0.014	0	0.04	0	0.14	1.976
July 19	0.47	1.44	T	0	0.01	0	0.04	0.570
Aug. 4	0.47	1.44	T	0	T	0	T	0
Aug. 5	0.57	1.20	0.002	0	T	0	0.07	0.302
Aug. 7	0.31	0.48	0	0	0	0	T	0
Sep. 17-19	1.40	3.60	.003	0	0.01	0	0.43	8.978
Oct. 5	0.83	...	.005	0	0	0	0.01	0.027
Total	7.95	...	0.024	0	0.06	0	0.69	11.853
1949								
July 5	0.35	1.20	0	0	0	0	0.10	0.838
Aug. 23	0.49	1.44	0	0	0	0	0.07	1.782
Total	0.84	...	0	0	0	0	0.17	2.620
Three-yr. total	11.50	...	0.024	0	0.06	0	1.19	18.659
Three-yr. average	3.83	...	0.008	0	0.02	0	0.40	6.220

[a] Precipitation during rainstorms that caused some overland flow as measured in an intensity gage.

variations in soil, vegetation, and climate must be considered cautiously. The plot data on water available for stream flow should apply quite satisfactorily to larger areas which have similar cover, precipitation, and soil. Such comparable conditions exist only in the higher parts of steep mountain watersheds between 7000 and 10,000 feet elevation. Here, where annual precipitation is greatly in excess of consumptive use, removing deep-rooted vegetation would increase water available to streams.

On the other hand, as elevation decreases and precipitation becomes less and less, a point is reached where consumptive losses approximately equal annual precipitation. Under such conditions, removal of deep-rooted species would probably have little, if any, effect on water yield.

Soil stability was maintained by the herbaceous vegetation and litter that remained after removal of aspen, but erosion from the bare sites was excessively heavy, being as much as six tons per acre per year. Such prohibitively heavy soil loss makes any concomitant gains in water yield of academic importance only.

The thin skin of soil on most watersheds has been untold ages in the making. To permit even a small amount to be lost each year in the interest of a minor addition to stream flow is unthinkable. Our soil capital on mountain slopes is so small that, even with a meager annual loss, in a few years all topsoil would be gone and with it the capacity of our mountain watersheds to produce timber and forage, regulate stream flow, and prevent reservoir sedimentation.

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SEA-WATER INTRUSION INTO GROUND-WATER BASINS BORDERING THE CALIFORNIA COAST AND INLAND BAYS

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Abstract--Sea water has already invaded or is an immediate or potential danger in at least 80 major and minor ground-water basins in California. Of this total, there is definite evidence of intrusion into 13 basins and immediate danger exists in seven additional basins. Where the normal seaward hydraulic gradient has been reversed for protracted periods of time, sea-water intrusion has occurred. Possible methods of control to restrain encroachment or reduce the area already affected include: (1) raising of ground-water levels to or above sea level by reduction or rearrangement of pattern of pumping draft, or both; (2) direct recharge of overdrawn aquifers to maintain ground-water levels at or above sea level; (3) maintenance of a fresh-water ridge above sea level along the coast; (4) construction of artificial subsurface dikes; and (5) development of a pumping trough adjacent to the coast. The California Legislature has appropriated $750,000 for an experimental program to determine design criteria for the prevention and control of sea-water intrusion.

Introduction--Extensive damage due to sea-water intrusion has already occurred in numerous ground-water basins adjacent to the coast of California, with resultant large economic losses. Unless means of prevention and control of this source of degradation are undertaken in the near future, further widespread deterioration of ground-water supplies will occur. Further intrusion can be prevented by decreasing the pumping draft on the coastal ground-water basins, but this may not be the most economic procedure. A comprehensive research program, carefully controlled and executed, comprising both laboratory and field experimental investigations, is necessary before the technical and economic feasibility of the other possible methods of prevention and control can be determined.

Status of sea-water intrusion--Encroachment of sea water has already occurred, or is an immediate or potential danger in at least 80 major and minor ground-water basins bordering the California coast and inland bays (see Fig. 1).

Areas of known sea-water intrusion--Sea water has encroached upon the coastal segments of 13 major and minor ground-water basins shown by the solid black in the legend of Figure 1. Water-bearing deposits in these basins may be either in direct contact with the ocean or bay floor or they may extend beneath the floor as a confined pressure aquifer and at some distance offshore be in contact with sea water. Due to excessive extractions of ground water, water levels along the seaward margins of these basins have been drawn down below sea level and the natural seaward hydraulic gradient has been reversed.

Areas of threatened sea-water intrusion--An immediate and serious danger of encroachment exists to the ground-water supplies in seven basins shown in Figure 1. Water-bearing deposits along the seaward and bayward margins of these ground-water basins are apparently open to the ocean; ground-water levels in the coastal areas have been below sea level for some period of time; a landward hydraulic gradient slopes inland from the coastal areas; and draft on ground-water supplies exceeds replenishment, particularly during drought periods. However, from information available at present, there is no definite evidence of intrusion. Saline water may already have displaced fresh water in the seaward or bayward extensions of the aquifers.

Areas of potential sea-water intrusion--There are 15 major ground water basins which are potential areas of sea-water intrusion (see Fig. 1). Water-bearing deposits in these basins are apparently open to sea water, but encroachment is restrained for the present due to ground-water levels in the coastal areas being at or above sea level and the existence of a seaward hydraulic gradient over the entire basin.

In addition, there are at least 45 small alluvium-filled valleys and coastal areas about which little is known. Their location indicates that potential danger of sea-water intrusion may be assumed to exist. The State Division of Water Resources is currently engaged in investigating all areas of possible sea-water intrusion.

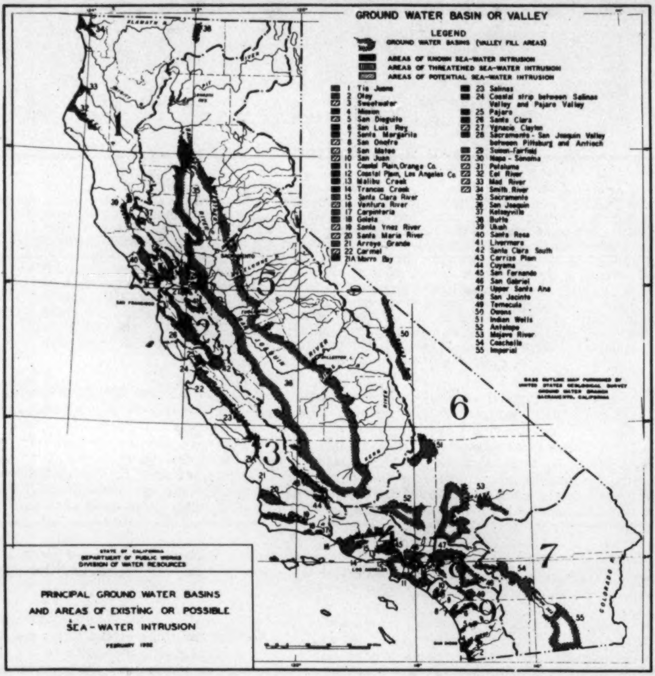
GROUND WATER BASIN OR VALLEY
LEGEND
GROUND WATER BASINS (VALLEY FILL AREAS)
AREAS OF KNOWN SEA-WATER INTRUSION
AREAS OF THREATENED SEA-WATER INTRUSION
AREAS OF POTENTIAL SEA-WATER INTRUSION
1 Tia Juana
2 Otay
3 Sweetwater
4 Mission
5 San Dieguito
6 San Luis Rey
7 Santa Margarita
8 San Onofre
9 San Mateo
10 San Juan
11 Coastal Plain, Orange Co.
12 Coastal Plain, Los Angeles Co.
13 Malibu Creek
14 Trancas Creek
15 Santa Clara River
16 Ventura River
17 Carpinteria
18 Goleta
19 Santa Ynez River
20 Santa Maria River
21 Arroyo Grande
22 Carmel
21A Morro Bay
23 Salinas
24 Coastal strip between Salinas Valley and Pajaro Valley
25 Pajaro
26 Santa Clara
27 Ygnacio Clayton
28 Sacramento - San Joaquin Valley between Pittsburg and Antioch
29 Suisun-Fairfield
30 Napa - Sonoma
31 Petaluma
32 Eel River
33 Mad River
34 Smith River
35 Sacramento
36 San Joaquin
37 Kelseyville
38 Butte
39 Ukiah
40 Santa Rosa
41 Livermore
42 Santa Clara South
43 Carrizo Plain
44 Cuyama
45 San Fernando
46 San Gabriel
47 Upper Santa Ana
48 San Jacinto
49 Temecula
50 Owens
51 Indian Wells
52 Antelope
53 Mojave River
54 Coachella
55 Imperial
BASE OUTLINE MAP FURNISHED BY UNITED STATES GEOLOGICAL SURVEY GROUND WATER BRANCH SACRAMENTO, CALIFORNIA
STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES
PRINCIPAL GROUND WATER BASINS AND AREAS OF EXISTING OR POSSIBLE SEA-WATER INTRUSION
SAN FRANCISCO
LOS ANGELES
1
2
3
5
6
7
9

Fig. 1--Principal ground-water basins and areas of existing or possible sea-water intrusion

Possible methods of control of sea-water intrusion--In the light of present knowledge and experience, there are five possible methods for the prevention and control of sea-water intrusion which will be discussed briefly, in turn.

(1) Raising of ground-water levels above sea level by reduction or rearrangement of pattern of pumping draft, or both--This method requires that the pumping draft be altered sufficiently either by reduction or by rearrangement of pattern of pumping, or both, that ground water levels will rise to or above sea level and be maintained there except possibly for infrequent periods of short duration. A seaward hydraulic gradient must be established and maintained. Insofar as is now known, this is the only method which would be wholly effective in all cases. However, in some instances, it would not allow the full development and utilization of the available ground-water storage capacity for water conservation. In some basins, raising the water table would decrease the inflow or supply to the basin while outflow or escape from the basin might be increased. A source of supplemental water supply of a quality suitable for direct use must be available.

(2) Direct recharge of overdrawn aquifers to maintain ground-water levels at or above sea level--This method requires that ground-water levels in the overdrawn aquifers be raised and maintained above sea level by artificial recharge through the application of supplemental water by surface spreading or injection wells, or both. One advantage gained by this procedure is that in some instances reclaimed waste waters of suitable quality could be utilized and in others flows which may be greatest at times of least demand can be stored underground until needed. If it is

found feasible to maintain ground-water levels above sea level by artificial recharging without change in pumping draft, it is possible that no determination of water rights or control of pumping would be necessary. For many of the ground-water basins along the coast, an expensive distribution and recharging system would be required. Operating expenses would probably be high. While a considerable body of experience and data concerning recharge by surface spreading is available, little is known about the feasibility of continued recharge through injection wells, particularly with reclaimed waters.

(3) Maintenance of a fresh-water ridge above sea level along the coast--This method would require the continuous maintenance of a fresh-water ridge in the principal water-bearing deposits along the coast through the application of water by surface spreading or injection wells, or both.

If hydraulically feasible, such a ridge of fresh water just inland from the coast would be as effective in repelling the intrusion of sea water as would an oceanward slope extending entirely across the basin. There would, of course, be some waste of water to the ocean. However, since greater lowering of the water table landward from the ridge would be permissible, greater development and utilization of the available underground storage capacity for water conservation could be achieved. Initial cost and operating costs would be high but would probably not be as great as would be incurred in attempting to keep water levels above sea level throughout the basin by direct recharge of the aquifers. To achieve maximum effectiveness at least cost, some rearrangement of the pattern of pumping might be necessary.

The construction of the ridge along the coastal segment of the basin by surface spreading or the use of injection wells will depend on whether free ground-water or pressure conditions exist. In basins where free ground-water conditions exist along the site of the proposed ridge, a mound of uniform height could be maintained by continuous application of water in the spreading grounds. In basins where pressure conditions exist and injection must therefore be through wells, the ridge would consist of a series of peaks with saddles between. In either case, the required elevation of the ridges and saddles would be determined by the fresh-water head necessary to displace ocean water to the base of the water-bearing deposits.

It is possible that reclaimed waste waters of suitable quality could be used to maintain such a ridge. Use of such waters appears to be the only solution that may be economically feasible in a number of ground-water basins where intrusion has already occurred or may occur, since other sources of the supplemental water needed to maintain the ridge are too expensive.

Much remains to be learned before the technical and economic feasibility of this procedure for the prevention of sea-water intrusion can be determined, particularly with respect to injection wells and the use of reclaimed waste waters. It is believed that, if found to be technically feasible, this method may prove to be the most economic solution for many of the larger ground-water basins, especially where large quantities of cheap reclaimed water are available.

(4) Construction of artificial subsurface barriers--This method would require the establishment of a subsurface barrier which would reduce the permeability of the water-bearing deposits sufficiently to prevent the inflow of sea water into the fresh-water strata. This reduction in permeability could be achieved by the construction of a subsurface barrier composed of sheet piling or a puddled clay cutoff wall. Injection of an emulsified asphalt, cement grout, bentonite, silica gel, or calcium acrylate might form a membrane of reduced permeability which would retard intrusion of sea water.

A subsurface barrier, although costly for the initial outlay, would probably be permanent. There would be no operation expense but some maintenance might be required. Such a barrier would allow the full development and utilization of the available underground storage capacity for water conservation. There would be no interference with existing pumping rights.

It is believed that such a subsurface barrier, if not initially too costly, may be the best solution for prevention of sea-water intrusion into many of the narrow coastal ground water basins, especially in those where the principal aquifers occur at relatively shallow depths.

(5) Development of a pumping trough adjacent to the coast--This method requires the continuous maintenance of a pumping trough along the coast in order to produce a localized seaward hydraulic gradient. It would add little to the usable storage capacity of the basin. The required installation and operation would be costly and unless a demand exists which could be satisfied with the mixed ocean and fresh water which must be pumped, considerable quantities of good water would be wasted. The only place where permanent utilization of this method might be justified is

in a basin where the recharge is itself sufficiently saline to require the waste of substantial amounts of water for maintenance of salt balance. The procedure might be applied temporarily, where encroachment is far advanced, to reduce the salinity before applying another method of control.

Experimental program of the California State Water Resources Board for the determination of design criteria for the prevention and control of sea-water intrusion--The California State Legislature during its 1951 session appropriated the sum of $750,000 to the State Water Resources Board for investigational work and study with the objective of formulating plans and design criteria for the prevention and control of sea-water intrusion into ground-water basins bordering the California coast and inland bays.

The investigational program as recommended by the Division of Water Resources and approved by the State Water Resources Board centers around the determination of factors necessary to apply the theories of the pressure ridge and reduction of permeability to a workable program for prevention and control of sea-water intrusion. It encompasses: (1) further studies of the basic nature and occurrences of sea-water intrusion; (2) hydraulics of injection wells and of the pressure ridge; (3) feasibility of use of reclaimed water in creating a pressure ridge; (4) feasibility of various techniques of grouting of aquifers to reduce permeability or to create a subsurface barrier; (5) feasibility of construction of puddled clay cutoff walls or similar types of subsurface barrier walls to depths in the order of 100 to 300 ft; and (6) evaluation of the economic factors involved.

The program is flexible and will be carried out to some extent on a step basis, each subsequent step depending on the results and findings of the previous work. The initial phase of the program will combine laboratory research with an applied field experimental study to determine the hydraulics and feasibility of creating a pressure ridge for restraining sea-water intrusion and methods for the reduction in permeability of water-bearing deposits. On completion of the initial experimental program, assuming creation of a ground-water pressure ridge is found to be hydraulically feasible, it is planned that an experimental program will be undertaken with the use of a reclaimed waste water for injection through wells.

The State Water Resources Board has contracted with the University of California, the United States Geological Survey, and the Los Angeles County Flood Control District for certain basic portions of this investigational program.

Work of the University of California--The studies to be carried out at Berkeley include: (1) an abstract of literature and development of theoretical considerations and relationships; (2) parameters of sea-water intrusion, such as shape and rates of travel of interface between intruding saline waters and displaced fresh water; (3) shape and height of pressure ridge and required height of ridge to prevent sea-water intrusion as related to such hydrologic variables as depth, permeability and thickness of aquifers, difference in specific gravity of liquids, and rate of injection; (4) methods of construction and type of well best suited for injection purposes; (5) hydraulics of injection and of injection wells as related to hydrologic variables; (6) effect of relative depth of penetration of injection wells into aquifer; (7) reduction in aquifer permeability through use of emulsions, silica gel, plastics, and other materials; (8) raising the elevation of a ground-water surface by rearrangement of pattern of pumping; and (9) determination of effective sealing agents that when mixed with earthen materials from an excavated trench will create a backfill material which will set-up with time and become impervious to the flow of ground water.

To date an abstract of literature comprising approximately 200 items covering injection wells, sea-water intrusion, model studies, ground-water flow, and cutoff walls has been completed. Experimentation concerning sealing agents for mixing with earthen materials taken from an excavated trench for the purpose of creating a backfill material which will set-up with time and become impervious to the flow of ground water has progressed to the point where tentative conclusions can be made. Two sealing agents appear to produce the desired impermeability when mixed with backfill material consisting of 10 to 15 pct silt and 30 to 50 pct sand. These two sealing agents consist of: (1) thick (seven per cent) bentonitic slurry, and (2) thin (4.3 pct) bentonitic slurry plus 20 pct asphaltic emulsion. Further investigation is proposed in order to determine sealing agents that are more economical than those mentioned above.

The University has also completed a model aquifer in a section which is four feet long, three inches wide, and six inches deep, and constructed of lucite. The model has inlet and outlet sections which can provide salt and fresh water at various pressures. It also has an injection well, observation wells, and transparent sides. This model is being used for the purpose of studying and photographing the interfaces of salt water intruded into a fresh-water aquifer for various hydraulic conditions. By means of this model it becomes possible to obtain a series of photographs showing the movement of fresh salt-water interface during a period of sea-water intrusion and also the movement of this interface back out toward the ocean when a fresh-water mound is built up by means of an injection well. The model aquifer consists of pure fine quartz sand. A solution of calcium chloride mixed with fluorescent dye will be used in the model to represent the sea water. With the use of ultraviolet light, the calcium chloride solution will fluoresce and thus permit the photographing of the fresh salt-water interface.

The studies to be made at the University of California in Los Angeles are field and laboratory investigations encompassing: (1) determination of the compatibility of recharge water with the existing ground water, that is, the chemical and physical changes resulting from mixing dissimilar waters such as exist in recharging an aquifer will be evaluated; and (2) determination of the sanitary engineering aspects of the well recharging program, that is, evaluation of the feasibility of controlling biological growths in porous media through chlorination, lime, copper, sulphate, and other chemical means and biologic processes.

At the present time the University of Los Angeles is engaged in operating 13 permeameters utilizing MWD (Metropolitan Water District) water. Unaltered MWD water is being percolated through a disturbed sample and four of the permeameters and acid-treated MWD water with a pH of about 5.5 is being circulated in the remaining four cores. The samples being used were obtained during the well-drilling program at the Manhattan Beach Experimental Project.

The University has found that both chlorine and acid treatment increases the percolation rate through formation cores obtained at Manhattan Beach. The improvement in the flow rate due to these treatments occurs after the marked decrease in permeability which takes place within the first 24 hours of operation. They are now engaged in ascertaining if both treatments are carried out simultaneously if the increase in percolation rate due to each treatment will be accumulative.

Work of the United States Geological Survey--The studies now being made by the U. S. Geological Survey are laboratory investigations encompassing: (1) determination of salt-intrusion indicators that will enable the differentiation between oil brines, connate waters, and sea-water intrusion; and (2) geochemistry of sea-water intrusion.

Work of the Los Angeles County Flood Control District--The studies now being made by the Los Angeles County Flood Control District under the present contract have been undertaken in West Coast Basin in the vicinity of Manhattan Beach. These studies consist of field investigations limited primarily to determination of basic factors and criteria involved in the creation of a pressure ridge by injection of fresh water into the underlying confined main water-bearing zone in the Pleistocene deposits, sufficient for the prevention of sea-water intrusion. Sea water has intruded these water-bearing deposits and is rapidly advancing inland. This experiment will comprise five 12-inch injection wells spaced 1000 ft apart, with four 12-inch observation wells located midway between the injection wells which can be used for injection should it prove necessary to use a spacing closer than 1000 ft. Thirty-six eight-inch observation wells will be situated so as to provide sufficient control for determination of the basic shape and other hydraulic features of the pressure ridge. The line of injection wells will extend one mile along the coast and are approximately one and one-quarter miles coastward from the saline front. Colorado River water, purchased from the MWD, will be injected. This experiment will be continued for a minimum of six months, and may be expanded if found necessary after the first six months of operation.

To date there have been nine injection and 36 observation wells drilled. The construction of the water distribution system has been completed. The project started water injection in February, 1953.

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SOME PRECIPITATION-ALTITUDE STUDIES OF THE TENNESSEE VALLEY AUTHORITY

James Smallshaw

Abstract--Three precipitation-altitude studies made cooperatively by the Tennessee Valley Authority and the U. S. Weather Bureau are discussed. In one study covering observations of a line of precipitation stations across the Great Smoky Mountains, a typical increase of rainfall with altitude is described. Results of another study, an investigation across sharp-crested Snake Mountain, North Carolina, show precipitation at the top of the ridge to be only 70 pct of that on the slopes a short distance below the crest. A similar situation is described on Clinch Mountain in Virginia. Seasonal effects are noted, with the most pronounced differences occurring in the October-March period. The low catch at the ridgetop stations is attributed to a combination of updraft and carry-over of moisture-laden air because of the steep slopes and narrow crest widths of the ridges.

Introduction--The southeastern portion of the Tennessee Valley is a region of high relief and sharp precipitation contrasts. This area, known physiographically as the Appalachian Mountain subregion of the Blue Ridge Province, occupies about 9000 sq mi of the basin and contains the headwaters of four of the important tributaries of the Tennessee River. Many of its ridges reach 4500 or 5000 ft in elevation, and a number of peaks exceed 6000 ft. Between the ridges lie sheltered valleys several thousand feet lower.

The mean annual rainfall over the Appalachian Mountain area is about 55 inches, only slightly more than the mean for the whole Tennessee River basin. Mean annual precipitation at stations within the area, however, ranges from as low as 39 inches in the valleys to as high as 93 inches on the ridges. In wet years, such as 1948 and 1949, differences of 40 to 45 inches in annual precipitation may occur in distances of three or four miles.

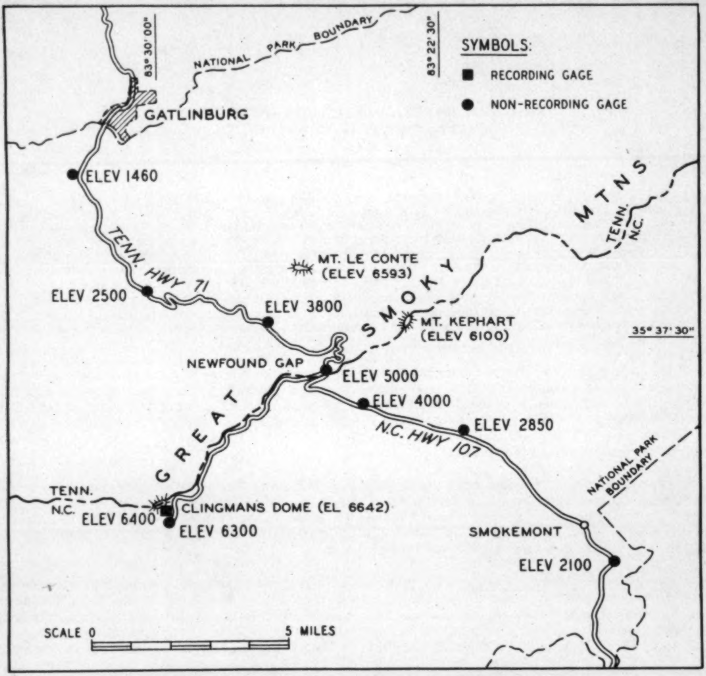
Great Smoky Mountain study--A typical example of precipitation increasing with altitude is found in the observations made cooperatively in the Great Smoky Mountains by the U. S. Weather Bureau, the National Park Service, and the Tennessee Valley Authority during the years 1946-1950. In connection with a study of snowfall on the mountains, standard non-recording precipitation gages with eight-inch collectors were established late in 1945 along the highway leading across Newfound Gap in the Great Smoky Mountains from Gatlinburg, Tennessee, southeastward to the vicinity of Smokemont, North Carolina. The location of the gages is shown in Figure 1. Existing standard non-recording gages near Gatlinburg and near Smokemont marked the two ends of the line. The length of the line was 18 mi, and the range in elevation was from 1460 to 5000 ft.

In 1947 another standard non-recording gage was installed five miles southwest of Newfound Gap on the southwest slope of Clingmans Dome at elevation 6300 ft, about 100 ft below a recording gage that had been in operation since 1935.

Since the study in the Great Smoky Mountains was primarily concerned with the measurement of snowfall, all of the eight non-recording gages were equipped with Alter shields. In addition, the gages were mounted on posts so that their top edges were from four to six feet above the ground to keep them above the level of accumulated snow. The recording gage on Clingmans Dome was a Friez weighing-recording rain gage, unshielded.

Figure 2 shows the variation of annual rainfall with altitude at the Great Smoky Mountain gages for each year of record and for the five-year average. The points indicated by circles are for gages on the northwest or Tennessee side of the ridge while the triangles indicate gages on the southeast or North Carolina side. The two Clingmans Dome records have been plotted but not used in drawing the curves since the exposure of these two gages is somewhat different from that at the others.

A very decided increase in rainfall with altitude is shown by these curves. During the five-year period an average of 31 inches more rain fell at Newfound Gap than at Gatlinburg, about nine inches for each 1000 ft of elevation. In 1946 the difference was 41 inches.



83° 30' 00"
83° 22' 30"
NATIONAL PARK BOUNDARY
SYMBOLS:
■ RECORDING GAGE
● NON-RECORDING GAGE
GATLINBURG
ELEV 1460
TENN. HWY 71
MT. LE CONTE (ELEV 6593)
ELEV 2500
ELEV 3800
GREAT SMOKY MTNS
TENN. N.C.
MT. KEPHART (ELEV 6100)
35° 37' 30"
NEWFOUND GAP
ELEV 5000
ELEV 4000
ELEV 2850
N.C. HWY 107
NATIONAL PARK BOUNDARY
TENN. N.C.
ELEV 6400
CLINGMANS DOME (EL 6642)
ELEV 6300
SMOKEMONT
ELEV 2100
SCALE 0 5 MILES

Fig. 1--Location of precipitation gages in Great Smoky Mountains

The effect of altitude appears from the data to be less pronounced above elevation 3000 or 3500 ft. The mean difference between the stations at elevations 1460 and 2500 ft was 12 inches, but between the stations at elevations 4000 and 5000 ft it was only five inches. The recording gage at elevation 6400 ft averaged only 2.5 inches more rainfall than the one in Newfound Gap at elevation 5000 ft. In Figure 3, the data have been reduced to seasonal averages. As might be expected, the effect of the mountain on precipitation was more pronounced during the winter season of general cyclonic storms than during the showery summer months.

Snake Mountain study--While precipitation in the Tennessee River basin generally increases with altitude, there are situations where this relationship does not hold true. An example was TVA's recording rain gage on Snake Mountain, at elevation 5600 ft, which consistently caught less rainfall than valley stations around it during 14 years of observation.

The Snake Mountain station, designated as No. 302 in Figure 4, was located on the eastern boundary of the Tennessee Valley just south of the Tennessee-North Carolina line. The Tennessee River valley lies to the west of the mountain on the map and the Kanawha River valley to the east.

On the Tennessee Valley side, Snake Mountain rises rapidly from a general valley elevation of 3200 ft to a very sharp north-south crest at an elevation just under 5600 ft. From the valley up to elevation 4400 ft the rise is about 150 ft in 1000, but above that point the slope increases to 500

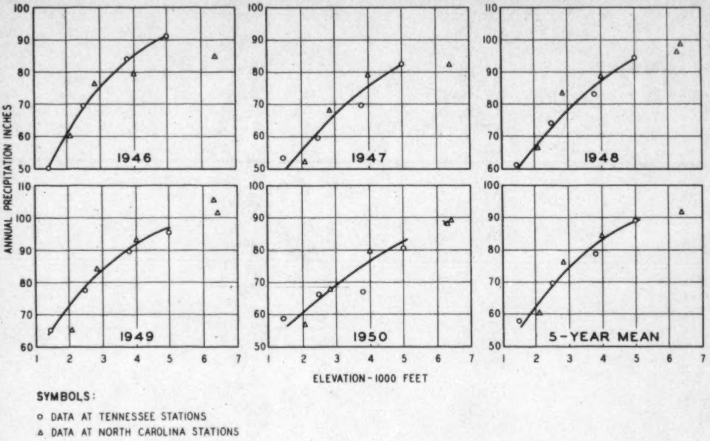


Fig. 2--Variations in annual precipitation with altitude at Great Smoky Mountain gages

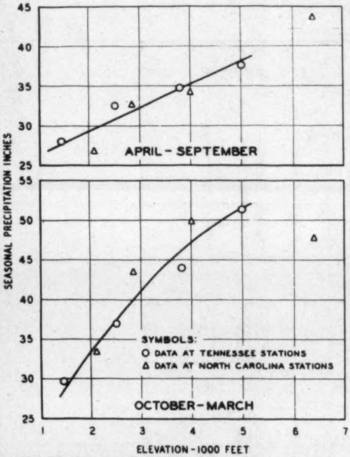


Fig. 3--Seasonal variations at Great Smoky Mountain precipitation gages; data are averages for the 1946-1950 period

ft in 1000. Slopes on the eastern side are similar. To the south the ridge drops off to Rich Mountain Gap at an elevation just above 4400 ft.

In November, 1946, three recording gages were established near the road leading across Rich Mountain Gap. These were at elevations 4350 and 4740 ft on the west slope and at 4780 ft on the east slope. Data at an existing non-recording station, No. 609, at elevation 3530 ft, were used as a measure of the precipitation at the foot of the mountain. Observations were continued at these gages for the two full years 1947 and 1948 and were terminated in April, 1949.

The three gages established in November, 1946, and the gage on top of the ridge were all Friez Universal rain and snow gages without shields. The TVA does not generally use shields on its recording and non-recording gages where snowfall is a small part of the annual precipitation. Since the original gage that was being checked was unshielded, no shields were used on the check gages.

The annual precipitation for 1947 and 1948 is shown in Figure 5 in relation to the profile position of each gage. Two ground-surface profiles are plotted, one through the three new gages, with No. 609 projected onto it, and a parallel profile through No. 302. Precipitation for the two years was very similar, the total for 1948 being almost identical with 1947. A

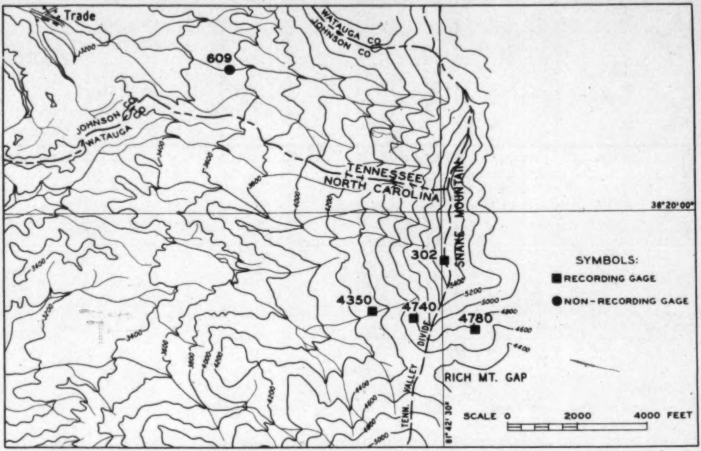

Trade
WATAUGA CO
JOHNSON CO
609
JOHNSON CO
WATAUGA CO
TENNESSEE
NORTH CAROLINA
SNAKE MOUNTAIN
36°20'00"
302
4350
4740
4780
DIVIDE
TENN. VALLEY
RICH MT. GAP
81°42'30"
SYMBOLS:
■ RECORDING GAGE
● NON-RECORDING GAGE
SCALE 0 2000 4000 FEET
3200
3400
3600
3800
4000
4200
4400
4600
4800
5000
5200

Fig. 4--Location of precipitation gages on Snake Mountain, North Carolina

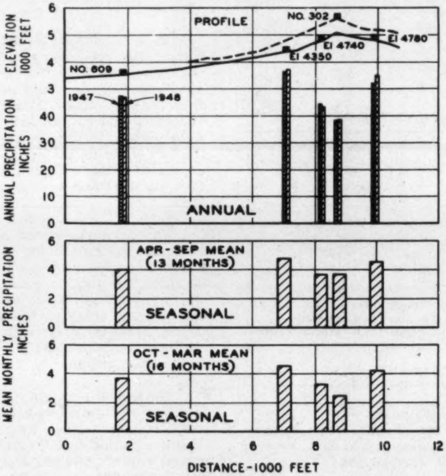


Fig. 5--Annual and seasonal precipitation on Snake Mountain, 1947-1948 typical altitude increase was found on the lower part of the west slope. The average increase in annual rainfall from the valley gage, No. 609, to the gage at elevation 4350 ft was 9.6 inches for a rise of 820 ft. This is at about the same rate per thousand feet that was noted on the lower slopes of the Great Smoky Mountains.

A definite reversal occurred above elevation 4350 ft, however. At the next recording gage, located only 400 ft higher, the average annual catch decreased 13 inches, and was 3.4 inches less than that in the valley. At No. 302 the annual precipitation decreased another 5.4 inches. The ridge-top gage thus averaged nine inches less annual rainfall than the valley station and 18 inches less than the gage at elevation 4350 ft. On the east slope the recorder at elevation 4780 ft caught 53 inches or very nearly the same as the station at elevation 4350 ft.

The lower part of Figure 5 shows that the pattern of precipitation across the mountain varied seasonally, the drop at the ridge-top gage being more noticeable in the October-March period than in the April-September period. The data on this part of the chart are mean monthly amounts for the 13 summer months and 16 winter months of record.

The low precipitation catch at the rain gage on top of Snake Mountain was attributed to a combination of updraft and carry-over of moisture-laden air because of the steep upper slope and the narrow crest of the ridge. The low catch at elevation 4740 ft was ascribed to the effect of updraft alone. It was probable that the location of this gage with respect to Rich Mountain Gap may have placed it in the zone of wind acceleration resulting from the funnel effect noted in the passes of most mountain escarpments. Under such conditions the gage would be subject to more than normal updraft.

It was obvious from the study that No. 302 was not suitable as a network gage and it was discontinued in May, 1949, in favor of the gage at elevation 4350 ft.

Spring Creek study--A condition similar to that at Snake Mountain was found on top of Clinch Mountain in southwestern Virginia at the Spring Creek recording rain gage. This part of the Tennessee Valley normally experiences lower rainfall than the rest of the Valley, but the Spring Creek gage had in 14 years of record established itself as a minimum point even for this area.

Clinch Mountain is a steep-sloped, sharp-topped ridge extending in the northeast-southwest direction typical of the Tennessee Valley and ridge province. The recording gage was situated on top of the mountain, just above a gap, at elevation 3200 ft. The ridge rises to elevation 3600 or 3800 ft on each side of the gap. The valley floors, about one mile away to the north and south, are at an elevation of about 2200 ft.

In May, 1949, three special gages were installed: an unshielded Friez Universal recording gage in the north valley, an identical gage half way up on the north slope, and an unshielded standard non-recording gage in the south valley. The gage on top of the ridge was also an unshielded Friez Universal gage. The distance between the north and south gages was only 10,000 ft with the old ridge-top gage almost exactly in the middle.

The total precipitation measured in 12 months of operation was 45 inches in the north valley, 46 inches on the north slope, 41 inches on top of the ridge, and 50 inches in the south valley. Practically all of the difference in precipitation occurred in the winter months, October through March. During the summer the rainfall at the ridge-top gage was rarely out of line with the other stations.

The data showed no increase with altitude. The mountain lies in the same direction as the prevailing winds, and it is not high enough to cause any important lifting effect. The deficiency at the ridge gage was ascribed to updraft along the very steep slope of the mountain with resulting carry-over of precipitation.

As a result of the Snake Mountain and Spring Creek studies, the TVA is avoiding the installation of network precipitation gages in or near mountain passes where funnelling of winds may be expected, or on top of high, sharp ridges with steep upper slopes. Both of these situations may give precipitation amounts less than that falling on the slopes only a short distance away.

Acknowledgments--The studies described in this paper were made cooperatively by the Hydraulic Data Branch of the Tennessee Valley Authority under the direction of Albert S. Fry, Branch Chief, and the Knoxville, Tennessee, office of the U. S. Weather Bureau in charge of T. W.

Kleinsasser, Meteorologist. The National Park Service cooperated in the observations made in the Great Smoky Mountains National Park.

The author is particularly indebted to Kleinsasser for his advice and help in interpreting the data.

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DISCUSSION

Walter T. Wilson (U. S. Weather Bureau, Washington 25, D. C.)--There are three general types of natural parameters which affect the variation in amounts of precipitation observed from place to place and from time to time. One of these types is the weather itself, in terms of areal distribution of condensation processes and types of circulation of and within storms. The second of these three types of natural parameters is topography, of a scale large enough to affect the weather itself. The third type of parameter expresses smaller scale terrain effects which are important largely through their influence on the performance of the measuring instrument itself.

These types of parameters can all be distinguished and their components evaluated by multivariate analysis of different kinds of precipitation data. Ordinarily this type of analysis requires more degrees of freedom than are provided by the small number of stations studied by Smallshaw. If station density is so sparse that a sufficient number of stations embraces a large area, then care must be taken to eliminate or account for the first type of parameter cited above: large-scale weather variation. This problem does not seem to exist in this study with respect to areal weather effects. However, seasonal variation in basic weather processes has been identified by Smallshaw. He has shown greater variance between topographic relationships (expressed entirely by altitude) for different seasons than exists within the relationship for each season. Smallshaw reasonably suggests the physical nature of the types of weather identified by season, largely in terms of stability of cloud systems.

The other type of relationship expressed by Smallshaw identifies ridge exposure as a small-scale influence on gage performance. It is not always easy to distinguish between the two general types of terrain parameters, and it might plausibly be argued that the diminished catch on high ridges is due to their effect on the weather or to decreasing charge of precipitable water in the air above some optimum height. Smallshaw's opinion that this is not the case is supported by many observations that gage catch is deficient on sharp ridges at all altitudes.

Smallshaw cites windy passes as well as sharp ridges as being poorly exposed sites for precipitation gages. Other types of poor local exposure can be listed and finally generalization is forthcoming on the basis of identifying places where there are sharp changes in wind vector. The adequacy of this statement may be judged from the fact that wind is the only dynamic factor affecting gage catch. Until quantitative analysis of exposure parameters is worked out, a falling or drifting snow is observed (or might be expected) to scour or pile up.

It is gratifying to see this practical application of the growing knowledge of precipitation-terrain-weather relationships.

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CALCULATION OF THE PERMEABILITY OF POROUS MEDIA FROM THEIR MOISTURE CHARACTERISTICS

N. Collis-George

Abstract--An interpretation of the moisture characteristic, or the relationship of moisture content to hydrostatic pressure deficiency, of a porous medium is outlined, giving the pore-size distributions involved in the simultaneous flow of a wetting and a non-wetting fluid. A method is described of calculating intrinsic permeabilities to air and water flow at all fluid contents.

When f (r), the pore-size distribution, of a porous medium is known, a theory has been proposed [CHILDS and COLLIS-GEORGE, 1948, 1950] enabling the calculation of permeability to water at any moisture content of the medium. The permeability, k, has been recently defined to be dependent on the properties of the medium and independent of those of the fluid. In such circumstances, k is named the "intrinsic permeability" of the medium and is defined by

$$v = -(k/\mu)\,\nabla\Phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where v is the velocity of fluid flow expressed as cc/sec per unit cross-section of total area, μ is the viscosity of the fluid, and $\nabla\Phi$ is the potential gradient [RICHARDS, 1952].

Considering f (r) dr as the quantity of pore volume filled by pores in the size interval r to r + dr, the intrinsic permeability, k_R, at that moisture content where the largest pores filled with fluid are of size R, is given by

$$k_R = m \sum_{\sigma=0}^{\sigma=R} \sum_{\rho=0}^{\rho=R} f(\sigma)\,dr\,f(\rho)\,dr\,\sigma^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where pores of radius $\sigma < \rho$, and m is a matching factor obtained by comparison of the calculated k_R with an experimentally determined intrinsic permeability at the same moisture content. Calculated and experimental permeabilities at saturation have given a relatively constant value of m for isotropic materials varying from 2 to 1 mm sands down to 1/8 to 0.04 mm diameter slate dust.

The method of summation to calculate k_R is detailed in Tables 1 to 3 of CHILDS and COLLIS-GEORGE [1950].

In these papers [CHILDS and COLLIS-GEORGE, 1948, 1950], the size of pore, r, and the volume of pores in the range r to r + dr, f (r) dr, were found by analysis of the curve relating pressure deficiency to moisture content, known as the moisture characteristic of the medium. Moisture characteristics of two materials, 1 to 1/2 mm sand and 1/8 to 1/25 mm slate, are given in Figure 1. Starting from saturated materials, they were obtained by a desorption method using porous sintered discs to apply increasing pressure deficiencies to the water contained in the medium; the water released by the medium was measured volumetrically. This type of apparatus is limited to suctions of 200 cm of water, and pressure-plate membrane apparatus [RICHARDS, 1947] can be used to extend the relationship to 180 atmospheres, provided certain precautions are taken [COLLIS-GEORGE, 1952].

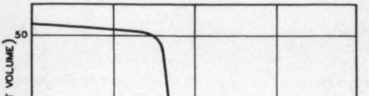

Fig. 1--Moisture characteristics of sand and slate dust, with values of film and lens water, V_x

Using the moisture characteristic, the pore size was equated to the reciprocal of the hydrostatic pressure to empty it. The matching factor, m, in (2) thus allows for surface tension and other factors. The size of pore so obtained, which for convenience we will call p, is related to the size of the neck of the pore, that is, to its narrowest dimension in the plane at right angles to flow, which in the theory is assumed to be the limiting dimension to flow since, by Poiseuille, permeability is proportional to r^4 for tubes.

On applying an increasing suction to the medium, the pores empty "in quanta" and not continuously, leaving air-filled pores that will not only contain lenticular rings of water where grains touch but will have a water film on their surfaces. The films being thin and bounded on one face by the solid matter of the medium and on the other by air, and the lenticular rings being isolated from one another by the films, cause the system to have negligible power to transmit water. In a water-filled pore, however, the boundaries of the water phase are those of the material of the medium and not the position of the air-water interface.

Using the moisture characteristic, the inferred volume of the pores is in fact the volume bounded by the air-water interface. For convenience, the volume of pores of size p, as determined by the moisture characteristic, we will call $\phi(p)\,dp$, to distinguish it from $f(r)\,dr$, the volume of pores of size r bounded by the solid medium.

In the earlier papers, no distinction was made between drainable pore water and "lens and film" water; the latter was considered as pore water only removable by high suction, that is, with $p \rightarrow 0$. The film and lens pores had negligible contribution to the summation for k_R because of their apparent smallness, and therefore the summation effectively began with the smallest true pore; the quantities used in the summation were, however, p and $\phi(p)\,dp$ instead of r and $f(r)\,dr$ as required.

To recapitulate, the moisture characteristic supplies the quantities p and $\phi(p)\,dp$, which, to be used in the summation, require increasing to r and $f(r)\,dr$ respectively. That is, the quantity film and lens water has to be distributed among the determined p and $\phi(p)\,dp$.

Let the volume of film and lens water, as distinct from water in full pores, be V_x. Firstly, considering several pore group sizes, the volume of water in films in each pore group will be proportional to the specific surface of each size group.

For a pore size r, $\frac{\text{Area of pore}}{\text{Volume of pore}} \propto r^2/r^3 \propto 1/r \approx 1/p$. But the total volume of all pores of size r is $f(r)\,r$. Therefore, the total surface area of pore group of size $r \propto f(r)\,dr/r \approx \phi(p)\,dp/p$. Therefore, the total surface area of medium $\propto \sum_{p=x}^{p=\infty} \phi(p)\,dp/p$, where x is the smallest water-filled pore. That is, any water still held in the soil at a suction greater than 1/x is held in the form of film and lens water. Therefore, the total volume of water held in the medium in the form of films, $V_F \propto \sum_{p=x}^{p=\infty} \phi(p)\,dp/p$.

Volume of film water in pores of size s, say

$$\text{Volume} = [V_F\,\phi(s)\,dp/s] \Big/ \sum_{p=x}^{p=\infty} \phi(p)\,dp/p \quad \text{(3)}$$

Secondly, the volume of water in the lens, on the other hand, is related to the dimensions of the pore by a polynomial expression, which for high pressures reduces to a simple linear relationship. The volume of water in lenses in pores of size s, say, is given by an expression similar to (3), in which the denominators s and p are replaced by s^2 and p^2, and V_F by V_L, where V_L is the total volume of water in lenses at pressure 1/x, and $V_L + V_F = V_X$.

Finally considering film and lens water simultaneously, a form of (3) would be expected with V_F replaced by V_X and the denominators to some power between one and two. In fact, calculations with denominators to the powers 2, 1, and 0 produce different distributions of film and lens water among the pores, but the effect of the different distributions on the matching factor and on the relationship of permeability to fluid content are almost identical for the media examined.

The method of distribution of film and lens water is obviously a second-order correction and not critical to the summation, and for convenience of calculation it is suggested that film and lens water be distributed in ratio of the volume of the pores, that is, with a denominator of unity in (3).

The thickness of the film will obviously increase the value of p to the value of r, but since the film is on a convex surface the film is restricted to molecular dimensions and for commonly encountered porous media, p = r. (For very fine porous bodies, for example, metals, it is doubtful if a moisture characteristic could be obtained, but in cases where this is possible a correction for the thickness of film is necessary.)

Putting p = r and distributing V_x as described, the moisture characteristic can be corrected to give the pore-size distribution of the media

$$f(r)\,dr = \phi(p)\,dp \times \left[1 + V_x \Big/ \sum_{p=x}^{p=\infty} \phi(p)\,dp\right] \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Note that the summation denominator in (4) equals P - V_x where P represents the total porosity of the medium.

$$f(r)\,dr = \phi(p)\,dp \times P/(P - V_x) \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

This correction makes little difference to the shape of the calculated curve of the relationship of permeability to moisture content but, of course, alters the value of the matching factor. When, however, the calculation of air permeabilities in porous media is considered, this interpretation of the moisture characteristic becomes important.

Considering air flow in a wet porous medium, the pores which are empty of water, apart from film and lens water, will be the larger pores in the system and the completely water-filled pores will be the smaller. In the calculation of air permeability at any particular air content, it is necessary to sum the interaction of pore sequences starting from the largest to the smallest contained in that air content, and as the air content increases so will successive sizes of pores emptied of water become smaller.

The pore volumes and pore sizes, which we have called ϕ (p) dp and p, as obtained from the moisture characteristic directly, will be satisfactory for the calculation of air permeability at a given ratio of content of air to water, since the pores open to air flow will in fact be bounded by the air-water interface of the film and lens water.

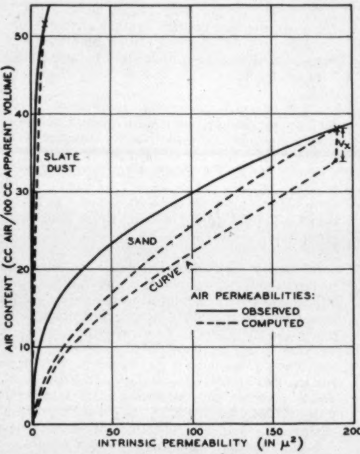

Fig. 2--Observed and calculated air permeabilities for sand and slate dust; Curve A is obtained when no correction for film and lens water is made and allows an estimate of V_x

Using these quantities, the summation can be completed from zero air content (or very large pores) to an air content of P - V_x. If the summation is continued to air saturation, disregarding the existence of film and lens water, on the assumption of V_x being distributed in the form of very small pores, it is found that the calculated permeability remains relatively constant between an air content of P - V_x and P, while experimentally permeability is increasing very rapidly in this region (see Fig. 2).

For air contents greater than P - V_x, it is necessary to consider the new interpretation of the moisture characteristic. When part or all of the film and lens water is removed, all pores become larger by amounts derived from (5), and the whole summation has to be repeated for each air content greater than P - V_x from the new largest to the new smallest pore in the system.

At complete water saturation, equal to P per cent, the water flow paths will be identical to the air paths in the completely dry medium; the volumes of the pore-size groups and the pore radii are identical in the two circumstances and the interaction summations although performed in different orders give the same absolute value of the sum and therefore of the matching factor.

It now remains to assign an interpretation and value to V_x, the volume of film and lens water at a suction $1/x$. On a smooth curve such as the moisture characteristic, V_x is not obvious by inspection.

Air permeability by theory, however, can be calculated up to an air content of $P - V_x$ without knowing V_x as a stage of the calculation. Consequently if the calculation is completed to P, the curve should show marked deviation from expected behavior at $P - V_x$. Curve A in Figure 2 is such a relationship of permeability to air content and allows an estimate of V_x to be made. With this value of V_x, the $f(r)\,dr$ necessary for water-permeability calculation are produced and the summation completed from zero to the largest pore. The value for the sum at water saturation is, of course, the value of the sum for maximum air permeability and the same matching factor immediately allows calculation of water permeability at all moisture contents from 0 to P per cent, and of air permeability from 0 to $P - V_x$ and the isolated value for P per cent.

The volume of film and lens water, as it has been derived and subsequently distributed among pores, implies that throughout the suction range the volume is constant. In fact, the volume of a lens is dependent directly on the pressure and consequently the amount of water removed from a pore at a low suction (that is, large pores) is smaller than if the pore could be emptied at a larger suction, say $1/x$. The distribution of V_x, as outlined, is likely to underestimate the effect of film and lens water for the larger pores. These pores are the most effective for permeability contribution and if correctly measured would produce maximum effect on the results of (2). In other words, if a truer picture of the pore-size distribution could be obtained than that of the corrected moisture characteristic as outlined, a better fit between calculated and determined permeabilities would be reached.

The summation for air permeability is most conveniently performed with a nine-column tabulation, with the columns respectively as follows: (1) p; (2) $\phi(p)\,dp$; (3) $\Sigma\phi(p)\,dp$; (4) $p^2\phi(p)\,dp$; (5) $p^2\phi(p)\,dp \times \Sigma\phi(p)\,dp$; (6) $2 \times \Sigma p^2\phi(p)\,dp \times \Sigma\phi(p)\,dp$; (7) $p^2[\phi(p)\,dp]^2$; (8) $\Sigma p^2[\phi(p)\,dp]^2$; and (9) $[2 \times \Sigma p^2\phi(p)\,dp \times \Sigma\phi(p)\,dp] - \Sigma p^2[\phi(p)\,dp]^2$. The first two columns are derived directly from the moisture characteristic, the largest pores heading the columns. The other column values follow directly from the quantities of the first two, and as each row is completed the last column is the required value of (2) for each air content, and when multiplied by the matching factor gives air permeability at each appropriate air porosity. After plotting the values of the last column against air porosity, a value of V_x is inferred and enables the production of the correct pore-size relationship, $f(r)\,dr$, by (5).

The summation for water permeability is then performed by some tabulation as follows, where the smallest pores head the columns respectively: (1) $p = r$; (2) $f(r)\,dr$; (3) $r^2 f(r)\,dr$; (4) $\Sigma r^2 f(r)\,dr$; (5) $f(r)\,dr \times \Sigma r^2 f(r)\,dr$; (6) $2 \times \Sigma f(r)\,dr \times \Sigma r^2 f(r)\,dr$; (7) $r^2[f(r)\,dr]^2$; (8) $\Sigma r^2[f(r)\,dr]^2$; and (9) $[2 \times \Sigma f(r)\,dr \times \Sigma r^2 f(r)\,dr] - \Sigma r^2 [f(r)\,dr]^2$.

Finally, by finding one value of the moisture content (generally saturation and marked on Fig. 2 and 3 by crosses) at which permeability is known, the matching factor, m, is found and hence the air and water permeabilities.

The calculated air and water permeabilities for the two materials are shown in Figures 2 and 3, together with experimentally determined values [COLLIS-GEORGE, in press] for these materials. A matching factor, m, of 35 μ^2 was used for the four theoretical curves in these figures. The values of V_x are shown in Figure 1.

Intrinsic permeability, although constant for all fluids at each saturation porosity, as

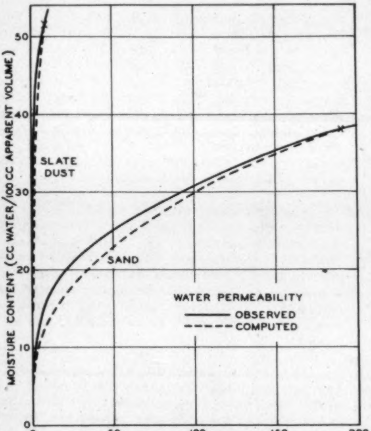

Fig. 3--Observed and calculated water permeabilities for sand and slate dust evidenced by the great use made of the Kozeny relationship, for example, ARTHUR and Others [1950], CARMAN and ARNELL [1948], WYLLIE and ROSE [1950], in the completely dry or completely wetted states, has two values for each fluid content in an unsaturated state (excluding hysteresis effects); one for the fluid which preferentially "wets" the surface of the medium and a greater one for the fluid non-adsorbed on the surface.

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THE CELERITY OF VERY LARGE FLOOD WAVES IN THE ARKANSAS BASIN

Charles D. Hopkins, Jr.

Abstract--Data show very large flood waves travel considerably more rapidly than flood waves of moderate size in certain rivers in the Arkansas Basin. A discussion of the possible causes and the practical implications follows.

One of the most difficult problems in the hydrology of rivers is the study of very large floods. Their characteristics are frequently almost freakish while their rarity makes it difficult to assemble enough data to learn those characteristics. At the same time, their behavior is of the highest order of importance.

In the course of studies of forecasts in the Arkansas River Basin the following fact was disclosed: As floods in certain rivers exceeded a certain magnitude, the apparent velocity of the flood wave increased. Forecasting procedures in use at present for the entire Verdigris, Caney, Neosho, and Cottonwood River Basins and in one reach of the lower Arkansas River include this effect.

Tables 1, 2, and 3 show tabulations of crest data and crest travel times for reaches of three different rivers. Some indication of the effects of inflow occurring within the reach is included in each case and crest travel times are included only for those cases where this local runoff can be assumed to have a negligible effect on the time of occurrence of the downstream crest.

In Figure 1, these data are presented graphically by plotting crest travel time versus the size of the upstream crest. A time-of-travel curve, drawn by inspection, is shown for each of the three cases.

This phenomenon is inadequately discussed in hydrologic and hydraulic literature. The treatment usually indicates that at low stages the travel time is long; as the stage and hydraulic radius increase, the travel time shortens to a minimum at some optimum stage; and above this stage, as the water spreads out over a shallow flood plain, the travel time again increases. However, at still higher stages the phenomenon discussed herein seems to occur.

A consideration of the probable causes of this phenomenon is an interesting exercise in speculative hydrology. The writer believes that the causes might be three in number: (1) changes in

Table 1--Crest data, Arkansas River, Van Buren to Dardanelle (in terms of flow)

Date of Van Buren crest	Crest flows[a]		Crest travel time	Computed local inflow on outflow crests[b]	Remarks
	Van Buren	Dardanelle			
	cfs	cfs	hr	cfs	
Apr. 22, 1941	301,000	294,000	36	2,000	
Oct. 18, 1941	200,000	220,000	36	5,000	
Oct. 28, 1941	202,000	207,000	30	0	Very flat
Nov. 3, 1941	485,000	433,000	60	0	
May 12, 1943	850,000	684,000	35	3,000	Maximum of record
May 23, 1943	750,000	680,000	48	0	
Apr. 18, 1945	650,000	584,000	48	3,000	
May 14, 1947	144,000	146,000	23	2,000	
May 25, 1947	185,000	194,000	21	2,000	
June 3, 1947	154,000	162,000	24	3,000	
June 26, 1948	330,000	299,000	27	6,000	
May 22, 1949	323,000	302,000	24	3,000	

[a] Approximate bankful flows: Van Buren, 140,000 cfs; Dardanelle, 180,000 cfs.
[b] Inflow from local area at Dardanelle at time of Dardanelle crest as computed from rainfall, rainfall-runoff relation, and unit hydrograph.

Table 2--Crest data, Verdigris River, Independence to Lenapah (in terms of flow)

Date of Independence crest	Crest flows[a]		Crest travel time	Local inflow[b]	Remarks
	Independence	Lenapah			
	cfs	cfs	hr	inch	
June 4, 1941	25,700	24,700	34	0.25	
Sept. 6, 1942	24,970	24,200	28	0.25	
May 7, 1943	21,700	28,000	32	0.22	
June 5, 1943	20,000	21,000	20	0.50	
May 20, 1944	31,800	29,100	39	0.38	
Apr. 24, 1944	56,000	53,500	46	. . .	Not much runoff at crest
Sept. 28, 1944	19,400	24,000	17	1.19	Not much runoff at crest
Dec. 6, 1944	26,040	24,500	39	0.91	
Mar. 26, 1945	27,800	25,400	42	0[c]	
Apr. 17, 1945	112,000	91,000	27	0[c]	
July 2, 1945	22,830	21,600	23	0.83	
July 1, 1951	100,000[c]	90,000[c]	30[c]	. . .	Not much runoff at crest

[a] Approximate bankful flows: Independence, 19,000 cfs; Lenapah, 30,000 cfs.

[b] Local inflow computed for storm period from hydrographs.

[c] Estimated from gage-height records at Independence and Claremore.

Table 3--Crest data, Neosho River, Iola (USGS) to Parsons (in terms of stage)

Date of Iola crest	Crest stages[a]		Crest travel time	Remarks
	Iola (USGS)	Parsons		
	ft	ft	hr	
June 3, 1941	27.7	25.0	100	Parsons crest very flat
June 12, 1941	23.0	22.7	63	Parsons crest very flat
Aug. 27, 1941	22.3	20.4	87	Parsons crest very flat
Apr. 25, 1944	32.3	29.7	56	
Dec. 8, 1944	29.9	26.2	120	
Mar. 26, 1945	22.6	21.1	38	
Apr. 18, 1945	31.9	29.0	65	
Aug. 11, 1945	18.2	17.8	50	
Oct. 1, 1945	23.8	24.5	52	Parsons crest very flat
June 24, 1946	19.0	18.7	35	
Mar. 14, 1947	19.8	19.7	42	
Mar. 17, 1947	18.7	18.8	34	
Apr. 5, 1947	25.6	23.1	74	
Apr. 15, 1947	26.2	25.0	75	Parsons crest very flat
July 23, 1948	34.6	30.2	55	See note [b] below
July 13, 1951	42.9	40.2	34	Maximum of record

[a] Approximate bankful stages: Iola, 19 ft (USGS); Parsons, 24 ft.

[b] A second and higher crest occurred from local inflow at Parsons during this flood without affecting first crest.

hydraulic radius, (2) changes in roughness, and (3) changes in channel length and steepness.

It is obvious that a very large flood will put water to some considerable depth over the flood plain. Since a flood plain in mature rivers has a definite, limiting width in the distance from bluff to bluff, a very large flood will have a much greater average depth than a moderate-sized flood. This in turn means that the hydraulic radius will be much greater.

It is an interesting possibility to consider the actual physical change in roughness in an overflow area during the course of a very large flood; structures of all kinds, trees, brush, crops, fence rows, and all manner of obstructions are swept away, laid flat, or buried under silt and sand. It is not unreasonable to suppose that a very large flood, with a deep, strong current across a flood plain, might increase its celerity by this process.

If the channel of a river meanders considerably, its valley length will be considerably shorter than its channel length. In that case, a very large flood, flowing as it does in the valley rather

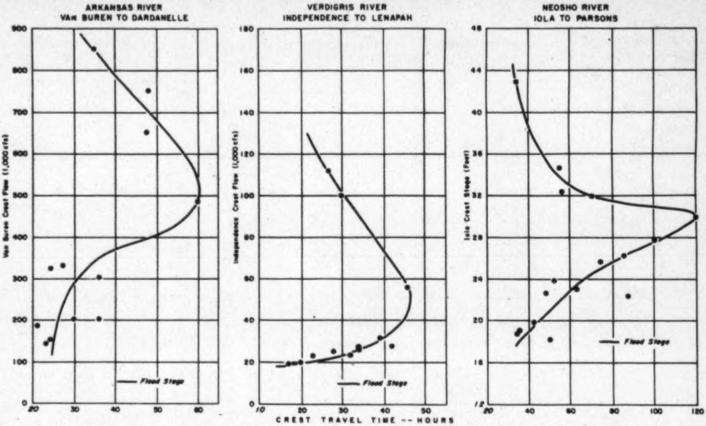

Fig. 1--Relationship of crest travel time to crest flow, Arkansas River Basin

than in the channel, would take considerably less time to proceed from one place to another, even if its real velocity remained constant. It should be pointed out, however, that the phenomenon of a lesser time of travel for very large floods can be observed in the Arkansas Basin for reaches with very little meander. The general effect is, however, much more striking in those reaches when considerable meandering is cut off during a very large flood. Such cutoffs, of course, steepen as well as shorten the reach.

Although these observations were made in the Arkansas Basin, it seems possible that similar effects occur in other rivers, at least in the Middle West. Evidently the Arkansas Basin, because of some peculiarity of the channel and valley sizes and the maximum observed floods, has proved an unusually rich source of data demonstrating the decreased time of travel of very large floods. Therefore, it is hoped that this note may prove a stimulus to hydrologists in other sections to realize that the strange behavior of a large flood may be not an isolated freak, but part of an easily recognizable pattern.

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ON TILTING MOTION OF GROUND OBSERVED BEFORE AND AFTER THE OCCURRENCE OF AN EARTHQUAKE

Eiichi Nishimura and Kennosuke Hosoyama

Abstract--A large secular tilting motion of the ground was observed with a tiltmeter at a station in the epicentral region three months before the occurrence of a destructive earthquake. After examination of the reliability of observation, the secular ground tilt of this kind is considered to be intimately related to the earthquake occurrence and may be useful for prediction of a destructive earthquake and mitigation of disaster.

On March 7, 1952, a destructive earthquake occurred at a point 20 km offshore in the open sea, southwest of Noto Peninsula in Ishikawa Prefecture, Japan. As is shown in Figure 1, its epicenter was at 136.2°E and 36.5°N. The total energy released is estimated to have been nearly 10^{23} ergs. For this destructive earthquake, the tilting motion of the ground observed at a station near the epicenter before and after the time of occurrence is reported and discussed. The observation room of the station is situated about 300 m under the ground surface in an adit of the Ogoya copper mine, which is 40 km distant from the epicenter (see Fig. 1). The main mountain rock is Tertiary tuff. Soon after the destructive Fukui earthquake on June 28, 1948, the continuous observation and recording with tiltmeter was commenced at this Ogoya station, 40 km from Fukui City. The purpose was to study the after effect of a destructive earthquake on crustal deformation in the epicentral region. Observations have been continued to the present time and furnish the data for the study of secular ground tilt in the epicentral region before and after the occurrence of the present destructive earthquake.

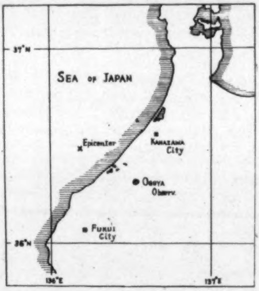

Fig. 1--Positions of Ogoya Observatory and the epicenter of the destructive earthquake of March 7, 1952

An important tiltgram of the four-day interval, March 4-8, 1952, bracketing the day of earthquake-occurrence on March 7, was not obtained because of an accident. It is regretted that we missed a chance to observe the phenomena forerunning the earthquake at a station close to the epicenter. Hence in this article ground tilt observed several hours before an earthquake occurrence such as was reported by SASSA and NISHIMURA [1951] can not be treated, but only secular ground tilt can be investigated.

In Figure 2 the secular change of A (NS direction) and B (EW direction) components of ground tilt observed at Ogoya during the last four years are plotted. The change during the epoch of no observations is provisionally plotted by a broken line to connect properly the data observed. Referring to the A component, the ground tilted a little to the north soon after the commencement of observation in July, 1948, and after two months turned its direction to South and continued tilting in the same direction during nearly two years. Since July, 1950, gradual tilting toward the north was again observed, and after ten months' interruption in the observations the A component showed large tilt to the north until the day of the earthquake occurrence. After that day the ground tilt to the north became smaller. Referring to the B component, the change of ground tilt during the first two years was very small. During the three months following the ten months' interruption, it showed minor fluctuations, but after December, 1951, the tilt toward the west became exceedingly large and continuous. This anomalous westward ground tilt continued to the day of the earthquake. After that day the tilt gradually turned its direction toward the east, showing more and more of a tendency to overcome the previous tilt to the west. It was ascertained by various examinations that these large secular changes were neither caused by the defect and error of the instrument nor by the local and particular motion of the concrete foundation or the adit of the mine. To show the

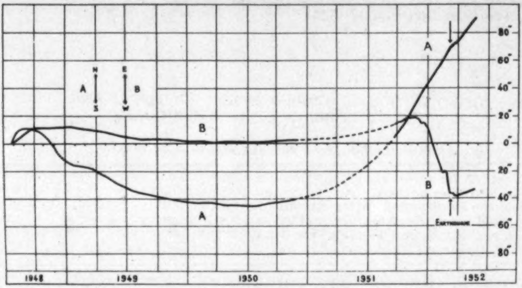

Fig. 2--Secular ground tilt observed at Ogoya; the arrows indicate the instant of earthquake occurrence on March 7, 1952

appearance of tilt at each stage, especially referring to the B component, three tiltgrams of different epochs are shown in Figure 3.

Combining the two components it appears that the ground at Ogoya commenced its tilting motion to the northwest three months before the day of the destructive earthquake, the epicenter of which was 40 km in a northwest direction from Ogoya. More rapid tilt to the northwest appeared ten days before and continued to the day of the catastrophe. Soon after that day the tilt suddenly became very much smaller and at present the ground is gradually coming back to the normal state.

It may be concluded that the large tilting motion of the ground observed at Ogoya three months, and especially ten days, before the day of the earthquake is intimately related to the destructive earthquake, and that the secular ground tilt of this kind is useful in studies to find a way to predict earthquake occurrence and mitigate the resulting disaster.

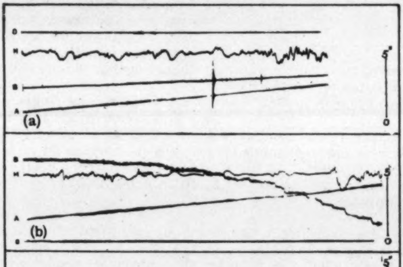

Fig. 3--Tiltgrams observed at Ogoya during the epochs (a) October 12-18, 1951, (b) February 18-25, 1952, and (c) May 14-22, 1952; the lines of A, B, M, and O correspond to change of ground tilt to NS- and EW-direction, change of magnetic declination, and datum line, respectively

For a detailed description of conditions of observation and strict examination of the reliability of observed data, refer to the paper by HOSOYAMA [1952].

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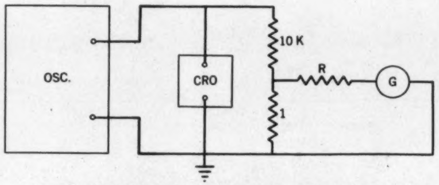
DYNAMIC TESTING OF SEISMOGRAPH GALVANOMETERS

Roger M. Wilson

Abstract--By using an ultra-low-frequency oscillator, a cathode-ray oscilloscope, and a high-frequency galvanometer it was possible to make frequency and phase calibrations of a seismograph galvanometer under simulated operating conditions. The methods are rapid and simple. It is proposed that such data could be combined with the mechanical and electrical constants of an "ideal" electromagnetic seismometer to derive the entire seismograph response curve from a single-frequency, shaking table test. Four design criteria for an ideal electromagnetic seismograph are stated.

Ever since Galitzin introduced the electromagnetic seismograph in 1911, the complete experimental calibration of such equipment has remained a major problem. The behavior of a seismograph pendulum system has been thoroughly investigated, both theoretically and experimentally, but efforts at a generalized analysis of the transducer-galvanometer system appear to have met with less success. MURPHY, PEARCE, BURGESS, and WILSON [in press; MURPHY and WILSON, 1952] collected considerable experimental data from which calibrations of certain galvanometers could be derived in the course of determining the response characteristics of an electromagnetic seismograph with the sine-wave simulator developed by Murphy. In this method the seismometer boom is forced to oscillate sinusoidally and the boom motion and galvanometer motion are recorded simultaneously. Partially as a result of this work the author became interested in the direct calibration of galvanometers under simulated operating conditions and undertook to develop the necessary techniques which were tested by making sample calibrations. After completion of his experimental work it was pointed out to the writer that the same results could be obtained by theoretical treatments involving only the circuit and galvanometer constants.

In 1951 the U. S. Coast and Geodetic Survey purchased an oscillator that has a range extending from 0.02 to 20,000 cps. This oscillator makes possible relatively simple calibration of a galvanometer under nearly any desired operating condition. Figure 1 shows the circuit arrangement used to make frequency response tests on a Rubicon galvanometer, Catalog No. 3500-S. This instrument was chosen because it was the most rugged and least critical to set up of the several that were available. Its characteristics are: period 1.58 sec (meas); coil resistance 10 ohms (rated); sensitivity 1.3×10^{-7} A/mm at one m (rated); CDRX 33 ohms (meas). The output of the oscillator was maintained constant by using an RCA WO-56-A oscilloscope as an indicator. The emf across



R=17 ohms for test with galvanometer overdamped
R=32 ohms for test with galvanometer critically damped
R=46 ohms for test with galvanometer damping ratio 25:1
R=58 ohms for test with galvanometer damping ratio 10:1

Fig. 1--Circuit arrangement for tests

the one-ohm resistance was thus essentially constant and the galvanometer response was obtained by recording short runs at various chosen frequencies. Complete tests were made at four selected galvanometer damping ratios, namely, 25:1, 10:1, critical, and over-damped. In the latter case the total circuit resistance was 65 pct of that required for critical damping. It will be noted that the general circuit arrangement is that used with the Galitzin or Sprengnether instruments, both of which employ a seismometer damping system that is independent of the generating system.

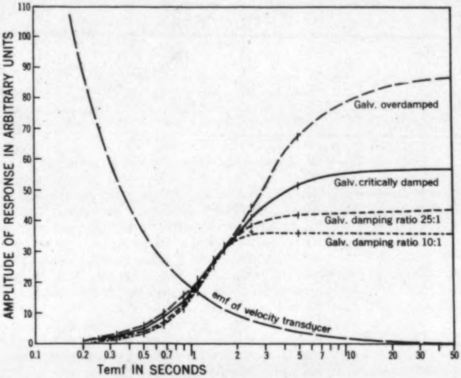


Fig. 2--Results of tests

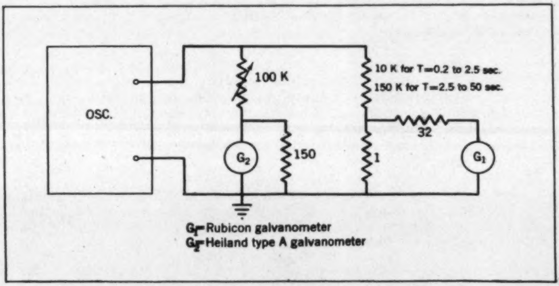

OSC.
100 K
10 K for T=0.2 to 2.5 sec.
150 K for T=2.5 to 50 sec.
32
G2
150
1
G1
G1-Rubicon galvanometer
G2-Heiland type A galvanometer

Fig. 3--Circuit for phase difference determination

The results are shown in Figure 2. The very great variation of the response with frequency may be somewhat surprising. It is possible that many will be surprised by the fact that the response of the over-damped galvanometer is greatest at all frequencies except those at or near the natural period of the galvanometer. This latter condition is peculiar to circuit arrangements that secure over-damping by means of low series resistance in the entire circuit or in the galvanometer branch rather than by shunting the galvanometer. It results from the increased coupling between the seismometer and galvanometer that exists in such circuits when the constants are such as to over-damp the galvanometer. The coincidence of all four curves in the vicinity of the natural period of the galvanometer is very interesting and confirms earlier results obtained with the sine-wave simulator.

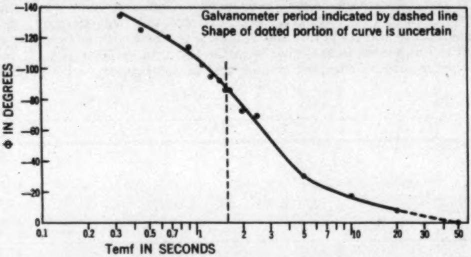


Fig. 4--Results of phase difference determinations

The phase difference between this galvanometer and its exciting voltage was determined with the circuit shown in Figure 3. The galvanometer was critically damped. The record made by a damped Heiland type-A galvanometer, period approximately 0.025 second, was used as a phase reference which was assumed to have negligible phase shift between 0.02 and 3 cps. The galvanometers were adjusted to have zero parallax difference and to record overlapping traces. The phase differences were scaled from the records and converted to degrees. Results are shown in Figure 4. To determine the phase difference between the Earth and the galvanometer, it is necessary to add the phase shift due to the pendulum to that determined by the electrical calibration.

Conclusions--Although all of the experimental work was done with a single galvanometer, there does not appear to be any obstacle to applying the method to any galvanometer operated under almost any desired conditions. It is believed that no significant error results from substituting the resistive simulated seismometer circuit for the actual seismometer coil, as the reactive component of the seismometer coil impedance is quite small in the case of most instruments throughout the teleseismic frequency range. This is not true in the case of a variable reluctance type of seismometer. In this case the seismometer may be blocked or clamped to prevent motion and the seismometer coil used in the circuit.

The over-all response curve of an ideal electromagnetic seismograph would be given by the product of the galvanometer calibration curve, the theoretical curve of the output of a velocity transducer (Fig. 2), the harmonic magnification curve of a simple pendulum of the same degree of damping as the seismometer, and a constant. A shaking-table calibration of such an ideal seismograph at a single period would be sufficient to determine the constant factor. Preliminary consideration of the matter indicates that this constant may also be determined by electrodynamic measurements that do not require a shaking table.

No actual electromagnetic seismograph can have ideal performance, but it may be made to approach this goal by using: (1) a heavy steady mass, (2) damping system independent of the generating system, (3) a generating system with small electrodynamic constant, and (4) a galvanometer with very small electrodynamic constant and moment of inertia.

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VOLUMES AND WEIGHTS OF PYROCLASTIC MATERIAL, LAVA, AND WATER ERUPTED BY PARICUTIN VOLCANO, MICHOACAN, MEXICO

Carl Fries, Jr.

(Publication authorized by the Director, U. S. Geological Survey)

Abstract--Estimates of the weights of pyroclastic material and lava erupted by Parícutin Volcano from early 1943 to early 1952 have given a pyroclastic weight of some 2230 million metric tons and a lava weight of about 1330 million metric tons, making a total of 3560 million metric tons of solids. The weight of pyroclastic material ranged from a maximum daily average of more than 10 million metric tons in the first two weeks of eruption to a minimum of some 65,000 metric tons in 1951. The weight of lava ranged from a maximum daily average of about 650,000 metric tons in 1943 to a minimum of some 170,000 metric tons in the second half of 1950.

The only period for which an estimate of the average daily weight of water vapor expelled by the Volcano could be made was the spring of 1945, when some 13,000 metric tons of water were expelled through the crater daily, besides some 500 metric tons contained in the lava extruded concurrently. Since the weight of pyroclastic material and lava erupted by Parícutin in the spring and summer of 1945 is estimated to have averaged about 1.2 million metric tons a day, the water expelled at that time amounted to about 1.1 pct of the total weight of material erupted. If the proportion of water had been nearly constant throughout the active life of the Volcano, the total weight of water would have amounted to some 39 million metric tons.

Introduction--Estimates of the weight of some of the solids erupted by Parícutin Volcano have been made for short periods of its life by various geologists, but no serious attempt to estimate the weight of water vapor erupted from the crater for any particular period was made until this was done by FOSHAG [1950]. The conclusions reached in that paper call for a more detailed analysis of the problem, as the implications arising from those conclusions are of considerable import to geologists working with igneous rocks and ore deposits.

The earlier published figures of the weight of solids are incomplete, and most of them are based only on rough estimates of cone dimensions or lava volumes for certain periods of time rather than on direct measurement and analysis or by careful triangulation; none of them seems to take into account the full significance of the great quantities of fine ash erupted by the Volcano. Sufficient data are now at hand to permit calculating with a moderate degree of accuracy the weight of solids erupted during almost any period of several months' duration in the nine-year life span of the Volcano. The writer feels that the presentation of these data is particularly desirable at this time, for all activity ceased on March 4, 1952, and eruptions now seem unlikely to resume.

Any estimate of the weight of water vapor must necessarily be restricted to certain relatively short periods when activity in the crater is not intermittently explosive but sufficiently stable or constant to permit adequate measurement. As pointed out by FOSHAG [1950, p. 751], such a period occurred in the spring of 1945, at which time the Volcano was in "average eruption" for the years 1944 and 1945. This period in the spring of 1945 will be used in the discussions that follow, for no later period when even rough measurements of water vapor could be made is known to the writer, who has probably seen Parícutin at more frequent and regularly spaced intervals in its nine years of activity than any other geologist.

Volume and weight of pyroclastic material--In the summer of 1946, SEGERSTROM [1950, pl. 1] made a series of ash-thickness measurements in the vicinity of the Volcano and prepared a map showing ash thicknesses in the area from the cone out to the 25-cm isopach. From a few measurements at selected points beyond the 25-cm isopach, he inferred that the eight-cm isopach passed through Los Reyes, the one-cm isopach through Jiquilpan, and the one-mm isopach through Guadalajara [SEGERSTROM, 1950, pp. 38-39]. (Foshag pointed out in a conversation with the writer that he felt that less than one cm of ash fell at Jiquilpan and that probably none fell at Guadalajara. Even if the greater part of the ash ascribed to the area beyond Los Reyes were discounted, however, the percentage of water vapor given in a later section of this paper would differ by only a few tenths

Table 1--Volume of ash deposited by Parícutin in different areas up to the end of August, 1946

Area[a] from isopach map		Size of area	Volume of ash
From	To		
m	m	million sq m	million cu m
Center of cone	30	1.1[b]	139.0[b]
30	12	1.6	34.2
12	11	0.4	4.1
11	10	0.4	3.9
10	9	0.5	4.5
9	8	0.6	5.1
8	7	0.9	6.3
7	6	1.3	8.3
6	5	1.7	9.2
5	4	2.9	12.8
4	3	5.7	19.9
3	2	11.3	28.2
2	1	31.7	47.6
1	0.50	56.0	42.0
0.50	0.25	104	39
0.25	0.08 (Los Reyes)	612	81
0.08	0.01 (Jiquilpan)	11,390	410
0.01	0.001 (Guadalajara)	46,460	204
	Totals	58,682[b]	1,099[b]

[a] See SEGERSTROM [1950, pl. 1, and p. 38].

[b] The number of significant figures used in this table and throughout the report indicates the relative reliability of the various quantities cited, except for some of the totals, which, used in other calculations, may indicate greater accuracy than meant by the writer.

of one per cent.) By means of planimetric measurements of the areas on the isopach map and reconstruction of the areas out to the eight-cm, one-cm, and one-mm isopachs, the writer recalculated the volume of ash deposited to the end of August, 1946, and found that the total volume amounted to about 1.1 billion cu m, as shown in Table 1. Some of the volumes given in this table differ from those in Segerstrom's Table 4, but as they were subjected to repeated checks by different methods, including a recheck by Segerstrom, they are believed to be as accurate as the basic data will permit.

In November, 1946, a few months after the isopach map had been prepared, Ray E. Wilcox began to keep daily ashfall records at Cuezeño station and at Equijuata or Jarátiro stations. The ashfall recorded at Cuezeño station from November, 1946, to June, 1947, was found to have the same ratio to the total ashfall at that station, as shown on the isopach map, as the ashfall recorded near Jarátiro during the same period had to the total ashfall at Jarátiro [SEGERSTROM, 1950, p. 37]. This ratio may not have been the same for all points at different distances from the cone at that time, and especially at later dates in the following months and years, when the average intensity of the eruptions was declining. The writer doubts, however, that any great error in order of magnitude would arise from assuming that annual volume increments for the years 1947-1951 over the whole area within the one-mm isopach of 1946 were directly proportional to the annual thickness of new ash that fell at Cuezeño station. Consequently, on the basis of Segerstrom's thickness determinations at the end of August, 1946, and the assumption that the ratio of the thickness of new ash at the end of each of the succeeding years to the 1943-1946 thickness was the same at different distances from the cone, the annual thickness of new ash at Cuezeño station was used to calculate the total volume for each year, as shown in Table 2. This table shows also the total volume of pyroclastic material up to the end of August, 1946, as given in Table 1. The volumes for the years 1947-1951 are naturally not as well controlled as the ones for 1943-1946, but the error in order of magnitude is felt to be less than 50 pct. Inasmuch as the period in which we are particularly interested is 1945, any error in volume calculations for 1947-1951 will not affect the value given later for the percentage of water in the magma that reached the surface in 1945.

Table 2--Volume and weight of ash deposited[a] by Parícutin for different periods on basis of ashfall records

Period	Duration	Ashfall at Cuezeño station	Total volume of ash	Average daily volume	Average daily weight[b]
	day	mm	million cu m	thousand cu m	thousand met tons
Feb. 20, 1943-Aug. 31, 1946	1288	480[c]	1099	850	1450
Sept. 1-Dec. 31, 1946	122	. . .[d]	33[e]	270[e]	460[e]
Jan.-Dec. 1947	365	43[f]	98	270	460
Jan.-Dec. 1948	366	12[f]	28	76	130
Jan.-Dec. 1949	365	9[f]	21	57	97
Jan.-Dec. 1950	365	7[f]	16	44	75
Jan.-Dec. 1951	365	6[f]	14	38	65

[a] In area out to one-mm isopach of 1946.
[b] A cubic meter weighs about 1.7 metric tons.
[c] See SEGERSTROM [1950, pl. 1].
[d] Ashfall records do not completely cover this period.
[e] Estimates based on Table 4, present report.
[f] Compiled from Parícutin activity reports published from time to time in these Transactions.

In order to learn something of the variations in average daily volume of ash during the period 1943-1946, an attempt was made to calculate the volume of the cone at different times and to establish a ratio between cone volume and total volume. The only dates in this period on which precise measurements of cone height or diameter, or of crater depth, were made are March 6, 1943, November 3, 1943, March 31, 1945, and July 27, 1946. Various estimates of cone height, diameter, or volume were made at other times during the period and have been published from time to time, but as these were not based on triangulation with precision instruments, and as calculations have shown them to be erratic or even unreasonable, they have not been taken into account in the calculations that follow. The dimensions used for determining the volume of the cone are given in Table 3, together with the increment in volume for each period represented. The measured volume on December 31, 1947, is also included to permit comparison with the values given in Table 2 and to cover a gap in that table. The diameter of the base of the cone increased in the first two years, but owing to the piling up of lava flows and accumulation of ash in the succeeding years, the apparent height of the cone and the diameter of the base decreased, as shown in Figure 1A.

Table 3--Dimensions and volume of cone at different times from 1943 to the end of 1947

Date	Maximum height of crater rim	Average height of crater rim	Average diameter of crater rim	Average height of base above ground[a]	Calculated average diameter of base	Average depth of crater	Total volume of cone	Volume increase since preceding date
	m	m	m	m	m	m	million cu m	million cu m
March 6, 1943[b]	137	110	216	12	520	70[c]	11	. .
Nov. 3, 1943[d]	282	255[c]	260[c]	40	900	85[c]	73	62
March 31, 1945[e]	342	315[c]	280	96	980	85[c]	124	51
July 27, 1946[f]	354	327	320	153	890	70	141	17
Dec. 31, 1947[g]	385	376	240	212	770	60	157	16

[a] Ground elevation at eruptive vent was about 2398 m above sea level.
[b] See FLORES COVARRUBIAS [1945, pp. 19-20, and lám. A].
[c] Estimated from descriptions, maps, or photographs.
[d] See FLORES COVARRUBIAS [1945, pp. 19-20, and lám. B].
[e] Unpublished triangulation data of Segerstrom.
[f] See SEGERSTROM and GUTIERREZ [1947, Fig. 2].
[g] See WILCOX [1948b, p. 355, Fig. 2, and Table 1].

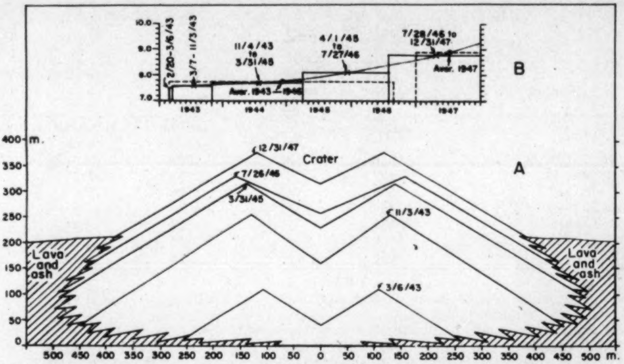

Fig. 1--Data on the cone: (A) sketch showing theoretical average cross section of the cone at different dates from 1943 to the end of 1947; (B) block diagram and curve showing average ratios of total pyroclastic volume to cone volume for different periods from 1943 to the end of 1947

The volume of the the cone was used to determine the total volume of pyroclastic material for each of the periods shown in Table 3. For this purpose, the average ratio of total ash volume to cone volume was determined for the period 1943-1946 and for the year 1947. The first ratio was found to be 7.73, and the second, 8.9. These two ratios were used to construct a curve for the period 1943 to 1947 (see Fig. 1B), from which the average ratios were taken for the periods given in Table 3. The form of the curve is admittedly subject to personal interpretation, and it may not actually be as shown in Figure 1B, but this form is the best that the writer could devise from all available data and repeated calculations by trial and error, and it is felt to be a reasonable interpretation of the data at hand. As a matter of fact, the curve could not be much different, and moderate changes in the ratios would not significantly affect the average daily volume of pyroclastic material for 1945, although they might appreciably affect the volume for 1943. It is notable that with declining average pyroclastic activity the cone-volume increment became a smaller part of the total ash volume erupted. By means of the ratios determined from the curve in Figure 1B and the cone-volume increments given in Table 3, the total volume of pyroclastic material was

Table 4--Volume and weight of ash deposited[a] by Parícutin for different periods, on basis of volume of cone

Period	Duration	Volume increase of cone for period[b]	Ratio of total volume to cone volume[c]	Total volume for period	Average daily volume	Average daily weight[d]
	day	million cu m		million cu m	thousand cu m	thousand met tons
Feb. 20-Mar. 6, 1943	14	11	7.5	83	5,930	10,000
Mar. 7-Nov. 3, 1943	242	62	7.6	473	1,950	3,300
Nov. 4, 1943-Mar. 31, 1945	514	51	7.7	395	770	1,300
Apr. 1, 1945-July 27, 1946	483	17	8.1	138	290	490
July 28, 1946-Dec. 31, 1947	522	16	8.8	141	270	460

[a] In area out to one-mm isopach of 1946.

[b] See Table 2 of this report.

[c] Based on curve obtained from two points, one for 1947 when the average ratio of total volume to cone volume was 8.9 for the year, and one for the period Feb. 20, 1943-Aug. 31, 1946, when the average ratio was 7.73.

[d] A cubic meter weighs about 1.7 metric tons.

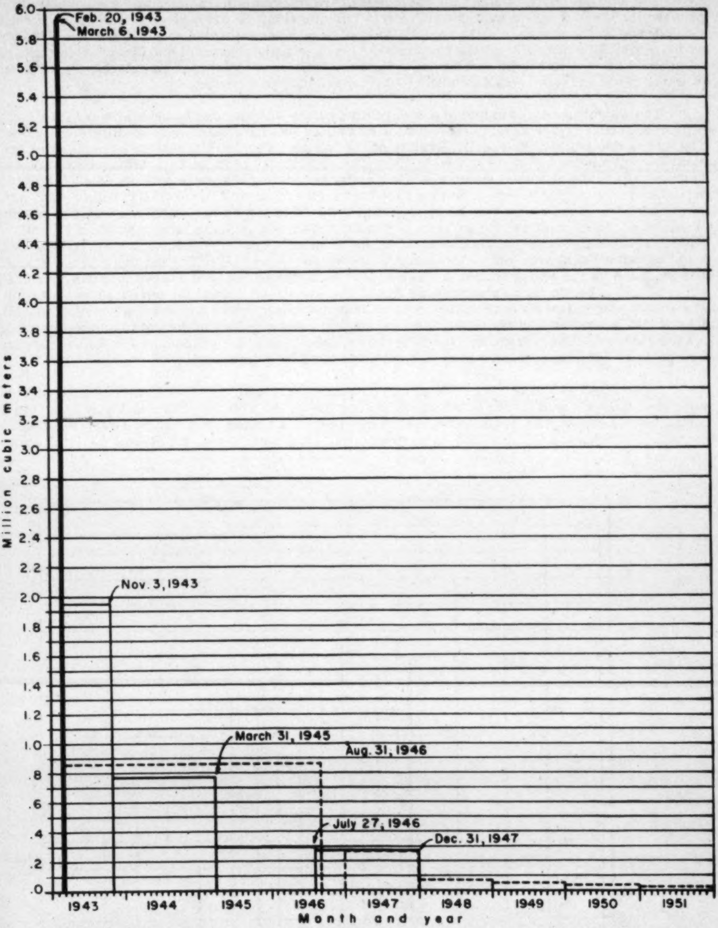

Fig. 2--Block diagram showing average daily volumes of pyroclastic material erupted by Parícutin for different periods from 1943 to the end of 1951; broken-line blocks are based on Table 2, and solid-line blocks on Table 4

calculated for each of the periods shown up to the end of 1947. These volumes, together with the calculated average daily volumes and weights for the same periods, are listed in Table 4.

The average daily volumes for each of the periods shown in Tables 2 and 4 were used to prepare the block diagram in Figure 2. From this diagram, the average daily volume of pyroclastic material in the spring of 1945 appears to have been somewhere between 290,000 and 770,000 cu m--probably nearer the smaller figure. An average daily volume of 400,000 cu m for that period seems to the writer to be a reasonable figure; it will be used later in calculating the percentage of water vapor in the magma extruded at Parícutin during that period.

The weight per unit volume of ash deposited by the Volcano can be determined with a fair degree of accuracy, for several independent measurements have been made of different factors. The writer determined the specific gravity of the ash particles in different size fractions of many samples collected at different places in 1946 [SEGERSTROM, 1950, p. 35]. Although the large particles, such as lapilli, have a lower specific gravity because of their vesicularity, the average ash deposited in the region seems to have a specific gravity of about 2.6. SEGERSTROM [1950, p. 98], on the basis of specific absorption experiments in the field and on the estimated specific retention of moisture, concluded that the porosity of the deposited ash, in place, averages about 33 pct. **FOSHAG** [1950, p. 751] reported that on weighing measured quantities of ash, a cubic meter was found to weigh 1.5 metric tons. According to the weight found by Foshag and the average specific gravity found by the writer for the individual particles, the porosity of Foshag's sample was 42 pct, which is felt to be too high as an average for all the pyroclastic material deposited by Parícutin. The writer judges that an average porosity of 35 pct, to accord with Segerstrom's experimental data, would be sufficiently high. On this assumption, a cubic meter of ash, in place, weighs about 1.7 metric tons. The average daily weight of pyroclastic material erupted by the Volcano during the spring of 1945 thus appears to have been about 680,000 metric tons.

Volume and weight of lava--The areas covered by the different lava flows extruded at Parícutin have been mapped month by month during the life of the Volcano. The best map covering the period from February 20, 1943, to the end of that year is a sketch prepared by Pérez Peña and Foshag [FOSHAG and GONZALEZ, in preparation]. This sketch does not reflect the total area

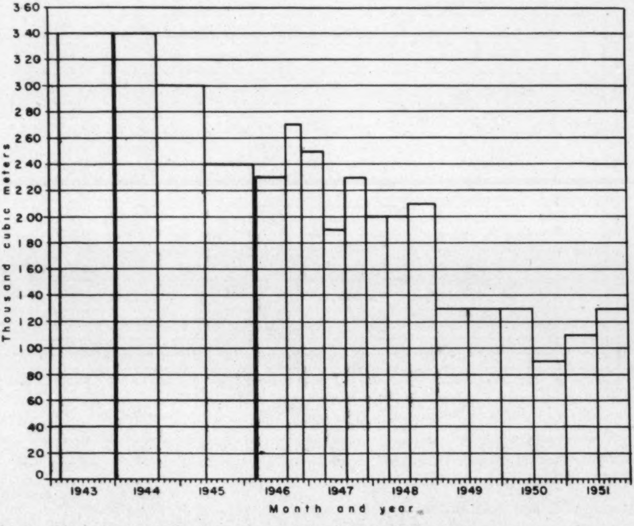

Fig. 3--Block diagram showing average daily volumes of lava extruded at Parícutin for different periods from 1943 through 1951

Table 5--Areas covered by Parícutin lava at different periods, and estimated volumes and weights of lava

Period	Duration	Area covered[a]	Estimated average thickness[b]	Total volume for period	Average daily volume	Average daily weight[c]
	day	thousand sq m	m	million cu m	thousand cu m	thousand met tons
Feb. 20-Dec. 31, 1943[d]	314	7,160	15	107	340	650
Jan. 1-8, 1944[e]	8	....	..	2.7	340	650
Jan. 9-Aug. 31, 1944[f]	241	13,770	6	83	340	650
Sept. 1, 1944-May 31, 1945[f]	273	13,840	6	83	300	570
June 1, 1945-Feb. 28, 1946[g]	273	9,360	7	66	240	460
Mar. 1-16, 1946[h]	16	....	6	3.2	200	380
Mar. 17-Aug. 31, 1946[i]	168	5,380	7	38	230	440
Sept. 1-Nov. 30, 1946[j]	91	4,020	6	24	260	490
Dec. 1, 1946-Mar. 31, 1947[k]	121	3,810	8	30	250	480
Apr. 1-July 31, 1947[l]	122	1,500	15	23	190	360
Aug. 1-Nov. 30, 1947[m]	122	2,300	12	28	230	440
Dec. 1, 1947-Mar. 31, 1948[n]	122	2,830	9	25	200	380
Apr. 1-July 31, 1948[o]	122	3,150	8	25	200	380
Aug. 1-Dec. 31, 1948[p]	153	4,050	8	32	210	400
Jan. 1-June 30, 1949[q]	181	2,440	10	24	130	250
July 1-Dec. 31, 1949[r]	184	2,640	9	24	130	250
Jan. 1-June 30, 1950[s]	181	2,260	10	23	130	250
July 1-Dec. 31, 1950[t]	184	2,080	8	17	90	170
Jan. 1-June 30, 1951[u]	181	2,560	8	20	110	210
July 1-Dec. 31, 1951[v]	184	2,820	8	23	130	250

[a] Planimetric measurements on published and manuscript maps.

[b] Estimated from personal observations or from published descriptions of flows; high values correspond to periods when lava piled up against topographic obstructions, or near ends of long flows, or was intruded beneath earlier flows.

[c] A cubic meter weighs about 1.9 metric tons.

[d] Sketch map by Pérez Peña and Foshag [FOSHAG and **GONZALEZ**, in preparation].

[e] Straight estimate.

[f] See KRAUSKOPF and WILLIAMS [1946, p. 407].

[g] See KRAUSKOPF and WILLIAMS [1946, p. 409].

[h] See KRAUSKOPF [1948, p. 1272].

[i] See SEGERSTROM and GUTIERREZ [1947, p. 565].

[j] See WILCOX [1947a, pp. 570-572].

[k] See WILCOX [1947b, pp. 728-729].

[l] See WILCOX [1948a, p. 72].

[m] See WILCOX and SHOUP [1948, p. 78].

[n] See WILCOX [1948b, p. 358].

[o] See WILCOX and **GUTIERREZ** [1948, p. 880].

[p] See FRIES and **GUTIERREZ** [1950a, p. 413].

[q] See FRIES and **GUTIERREZ** [1950a, p. 414].

[r] See FRIES and **GUTIERREZ** [1950b, p. 738].

[s] See FRIES and **GUTIERREZ** [1951a, p. 220].

[t] See FRIES and **GUTIERREZ** [1951b, p. 580].

[u] See FRIES and **GUTIERREZ** [1952a, p. 99].

[v] See FRIES and **GUTIERREZ** [1952b, p. 731].

covered by all the individual flows of that year, for observations were not continuous, some of the flows were masked by the heavy ashfall, many small flows were superposed, and much lava was intruded beneath earlier flows. Without precise detailed maps of each of the individual flows, the thickness of lava in areas where flows were superposed or were lifted by intrusion cannot be estimated with any great degree of accuracy. Taking into account the piling up of lava behind topographic obstructions, and the intrusion and lifting of the earlier lavas, an average thickness of 15 m for the area shown on the Pérez Peña-Foshag sketch is felt to be a conservative and reasonable estimate. On this assumption, the volume of lava for the period in discussion was about 107 million cu m, which represents an average daily volume of about 340,000 cu m, as shown in Table 5 and Figure 3.

From January, 1944, on, the individual flows were mapped in greater detail; later mapping was further controlled by a triangulation net established by Segerstrom for preparing a topographic map from vertical aerial photographs taken in the spring of 1945, under a grant of the Geological Society of America. Areas covered by individual flows from January, 1944, until the end of 1951 were mapped at different times by Krauskopf, Williams, Segerstrom, Wilcox, and Gutiérrez, aided by Pérez Peña, Molina Berbeyer, García Gutiérrez, Shoup, Hernández Velasco, and Saldaña. Inasmuch as different geologists prepared different maps, errors due to personal factors probably cancel each other; the limit of error may not exceed 15 pct for any three-month period. The writer has chosen an average lava thickness for each period shown in Table 5 and Figure 3, on the basis of published descriptions of the flows, or from his own observations. The flows of 1944 to 1946 were thinner than those of more recent years because the viscosity of the lava increased gradually. Where flows were obstructed by high ground, or near the ends of very long flows, the lava tended to pile up into layers as much as 30 or even 40 m thick. Although the average thickness given for each period is an estimate, the writer feels that the maximum error for any period is less than 50 pct. The estimated volumes of lava extruded during the different periods shown in Table 5 and Figure 3 are therefore subject to errors in mapping and in estimating the thickness. In general, however, the volume figures are felt to be reasonable and probably low rather than high.

It is interesting to note that the volume of lava extruded at Parícutin was well over 300,000 cu m per day for the first two years and that it held close to 200,000 cu m for the following three years. From then on, it dropped gradually to about 100,000 cu m per day in 1950. It increased again in 1951, especially in the second half of the year, and until all lava activity ceased on February 25, 1952. The fact that periods of great pyroclastic production were more or less coincidental with periods of great lava emission suggests that the intensity of explosive activity in the crater was governed to a great extent by the volume of magma reaching the surface. This relation is well illustrated by the spurt in lava volume and explosive activity in the second half of 1951. In the year 1945 the average daily emission of lava was well over 200,000 cu m, and in the spring of that year, during the period for which the water vapor weight was calculated, the average daily emission of lava was probably about 280,000 cu m.

The weight of lava per unit volume cannot be determined as accurately as the weight of ash per unit volume. Although pieces of dense lava without vesicles were found to have a specific gravity of about 2.7, the average lava is vesicular and has a lower specific gravity. Somewhat vesicular blocks of what the writer considered to be average lava were collected from different flows; their average specific gravity, which was 2.4, indicates that the average lava has a natural porosity of about 11 pct in the form of vesicles. FOSHAG [1950, p. 751] estimated the porosity of the lava

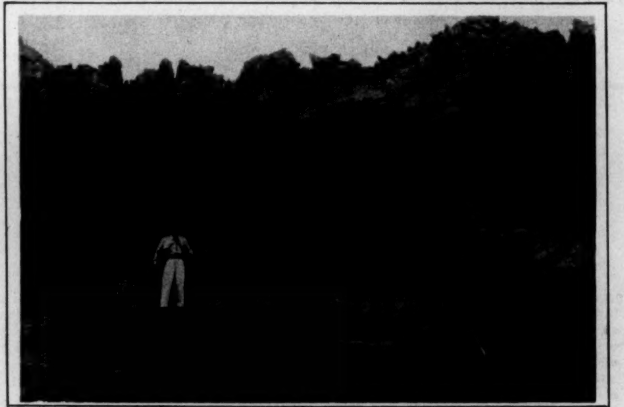

Fig. 4--Photograph of cross section of 1944 lava flow exposed near Curupichu, east of Parícutin cone, where storm waters have eroded back into flow; note massive interior and thin, rubbly top layer to be about 50 pct; this estimate includes the open spaces in fissures cutting the flows and in the loose rubble on top and at the bottom of the individual flows. A cross section of some of the flows can be seen in places where arroyos have eroded the edges of the lava field during the rainy seasons in the past eight years. From such exposures (see Fig. 4) the writer doubts that the open spaces in fissures and between blocks on top and beneath the individual flows would, on the average, exceed 20 pct of the total volume of the flows; they might be even less. On this assumption, the total porosity would be about 30 pct and the weight per unit volume of lava would be about 1.9 metric tons per cubic meter. The average daily weight of lava extruded in the spring of 1945 thus appears to have been about 530,000 metric tons.

Summary of volume and weight of pyroclastic material and lava--From the values given in Tables 2 and 4, Parícutin appears to have erupted at least 1310 million cu m of pyroclastic material from the beginning of its activity up to the end of 1951, two months before activity ceased. This volume does not take into account the finest material erupted that was carried by the winds beyond Segerstrom's one-mm isopach of 1946, but it probably represents at least 90 pct of the total pyroclastic material erupted. Using the average weight per unit volume given in the present paper, the weight of pyroclastic material up to the end of 1951 was at least 2227 million metric tons. The yearly volumes and weights of pyroclastic material are given in Table 6, which was prepared from the data in Tables 2 and 4. The average daily weight in 1945 was about 690,000 metric tons.

Table 6--Total weight and average daily weight of pyroclastic material and lava erupted at Parícutin, by years, from 1943 through 1951[a]

Year	Duration	Ash		Lava		Total weight	Average daily weight
		Volume	Weight	Volume	Weight		
	day	million cu m	million met tons	million cu m	million met tons	million met tons	thousand met tons
1943	314	601	1022	107	203	1225	3900
1944	366	280	476	122	232	708	1930
1945	365	148	252	98	186	438	1200
1946	365	103	175	87	165	340	930
1947	365	98	167	79	150	317	870
1948	366	28	48	76	144	192	520
1949	365	21	36	48	91	127	350
1950	365	16	27	40	76	103	280
1951	365	14	24	43	82	106	290
Totals and averages	3236	1309	2227	700	1329	3556	1100

[a] Calculated from values given in Tables 2, 4, and 5.

From the values given in Table 5, Parícutin appears to have extruded about 700 million cu m of lava from its inception to the end of 1951. This total is subject to confirmation or correction from topographic maps: one map, which is already prepared but has not yet been published, of the pre-eruption topography, and another map, for which plans are being made, of the post-eruption topography. Based on the average weight per unit volume given in the present paper, the total weight of lava extruded was roughly 1330 million metric tons. The weight of the average daily extrusion of lava during the year 1945 appears to have been about 510,000 metric tons.

The total weight of both pyroclastic material and lava erupted at Parícutin, as shown in Table 6, amounted to 3556 million metric tons up to the end of 1951. About 40 million metric tons of material was probably erupted in the remaining two months of the Volcano's activity, making the total weight during the life span of Parícutin about 3596 million metric tons. The average production of solids during the entire life of the Volcano was, therefore, 1.1 million metric tons per day. The yearly weights are given in the block diagram in Figure 5, and the average daily weights by year are given in the diagram in Figure 6. The average daily emission during 1945, the year for which the weight of water in the magma that reached the surface is calculated, was about 1.2 million metric tons.

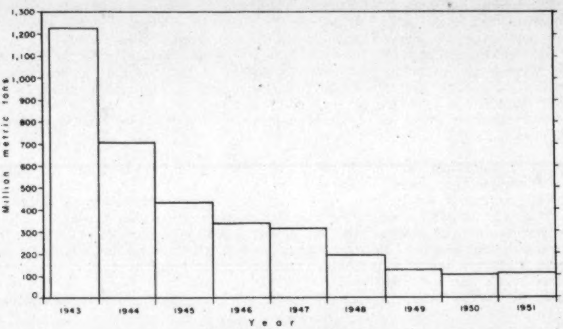

Fig. 5--Total weights of pyroclastic material and lava erupted at Parícutin, by years, 1943-1951

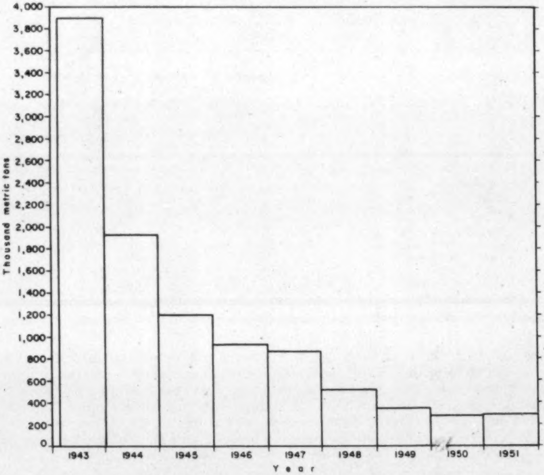

Fig. 6--Average daily weights of pyroclastic material and lava erupted at Parícutin, by years, 1943-1951

Weight of water vapor expelled through the crater--The writer first visited the crater of the Volcano on May 27, 1945, and revisited it from three to six times a year until May, 1951, when explosive activity became so violent and unpredictable that trips to the crater were extremely hazardous. During the spring and summer of 1945 the eruptions were fairly constant and the emission of gases was subject to some type of rough calculation. The writer knows of no later period in the life of the Volcano when conditions were equally good for making calculations of the volume of gases emitted from the crater, and hence he will follow Foshag in using that period for his calculations.

On May 27, 1945, the crater had two separate funnel-shaped vent areas aligned in a northeast-southwest direction, as it had been during most of the life of the Volcano, except during 1949-1951, when it generally had only one vent area. The northeast vent had one principal throat about two meters in diameter, from which a continuous stream of vapors issued at high velocity; the southwest vent consisted of a deep funnel with a hole in its bottom 10 m or more across, from which an enormous blast of ash- and bomb-laden vapors erupted every few hours. FOSHAG [1950, p. 751] has described this general type of activity as characteristic of the greater part of the years 1944 and 1945, although periods of stronger and weaker eruptions must have occurred from time to time; certainly the eruptions in 1944 were stronger on the average than those in 1945. Whether the volume of vapors emitted on May 27, 1945, represented an average daily volume for the year 1945 is, of course, open to question; the writer feels, however, that the average daily volume for that year was probably of that order and has found no other means of calculating this volume.

The only vapors issuing from the crater on May 27, 1945, that were subject to volume measurement, rushed from the two-meter throat described. Other vapors arose from different parts of the interior of the crater, and the southwest vent emitted vapors with each of its long-spaced eruptions. These were not subject to measurement, but in all they were certainly of minor volume compared with the main column. The lava vent emitted some water vapor, and the hot moving lava also gave off some water. However, the main column is felt to have accounted for at least 80 pct of the total water vapor given off to the atmosphere by the Volcano on that day.

The continuous stream of vapor issuing from the main vent carried some rock and lava fragments with it, and those that rose highest required about ten seconds to fall back to the altitude of the vent. Assuming that such pieces measured ten cm in diameter and, being quite vesicular, had a specific gravity of 2, the terminal or greatest velocity reached on falling back to the ground may be calculated by the following equation [HARDINGE and FRANKISH, 1945, pp. 02-03]

$$V_T = 71[a(S - p)/p]^{1/2} \quad \ldots\ldots (1)$$

in which V_T is the terminal velocity under turbulent conditions (high speed), 71 is a constant obtained experimentally for irregular fragments of quartz, a is the radius (5 cm) of the fragment, S is the specific gravity (2.0) of the fragment, and p is the density (0.00092) of dry air at 15°C, 2750 m above sea level. (The value of p would not change significantly at the relative humidity of the air around the Volcano on a clear day.) Substituting the appropriate values in this equation, we have $V_T = 71[5(2.0 - 0.00092)/0.00092]^{1/2} = 74$ m/sec.

The fragment would fall the distances shown in Table 7 in successive seconds from the top of its arc, reaching terminal velocity at the end of eight seconds. The height to which the fragment was hurled was thus about 462 m above the vent.

Table 7--Distance of fall in successive seconds

Interval	Distance per second
sec	m
1	4.9
2	14.7
3	24.5
4	34.3
5	44.1
6	53.9
7	63.7
8	73.5
9	74
10	74
1-10	462

The velocity at which the bomb left the vent may be calculated by $v = 2gs^{1/2}$, in which g is the acceleration of gravity (9.8 m/sec^2) and s is the total distance (462 m); it is computed to be 95 m/sec. Terminal velocity does not enter into this calculation, as the initial velocity was not limited by air resistance.

The gases must have streamed past the fragment at the orifice of the vent at a velocity equal to the terminal velocity of the fragment in the gases issuing from the orifice. This terminal velocity depended upon the temperature, composition, and pressure of the gases at the orifice. Inasmuch as the walls of these gas jets in the crater were a bright red and the fragments hurled out were red or even yellowish red, the temperature of the gases at the vent must have been in the range of 600°-1000°C. The following calculations are made for 600°, 800°, and 1000°, although the writer feels that the temperature was probably nearer 800° than the other two figures, for expansion in the throat below the orifice would have cooled the gases somewhat, but not below the temperature of the walls at the orifice. The temperature would drop exceedingly rapidly, however, the moment that the gas left the vent. The gas jet was visible immediately upon its leaving the vent, owing undoubtedly to condensation of water vapor in the form of a thin envelope around the jet. The presence of this vapor should not be interpreted to mean that the gases left the orifice at a temperature of 100°C or less.

The composition of the gases erupted through the crater is not known, for no means of sampling them could be devised because of the violence of the eruptions. The major compound was certainly water vapor, but whether this formed 80 or 99 pct of the total is not known. The odor of the gases indicated the presence principally of sulfur as H_2SO_4 and chlorine as HCl. CO_2 must surely have been present, and H_2S was noted on rare occasions. Probably some nitrogen and other inert gases were also expelled, and ammonium and other chlorides formed a part of the whole. For the purpose of calculation, the gases will be considered as having consisted of pure water vapor, for the molecular weight of the other minor gaseous compounds would not significantly affect the calculations of terminal velocity. Very fine ash particles were also present in the column and must have had the effect of increasing the density of the gases.

The pressure at the orifice is more difficult to determine. The writer assumes that the pressure of the gases at the moment they left the orifice was that of the atmosphere at 2750 m above sea level. If a greater pressure existed, the final values for weight of water vapor would be affected somewhat, but this effect would not be as great as one might think, because an increase in pressure would call for a greater density of water vapor and a lower velocity, which would mean that the gases would weigh more per unit volume, but that a smaller volume would leave the orifice per second.

To calculate the velocity at which the gases would stream past a ten-cm fragment held at a constant elevation at the orifice, the formula for terminal velocity is the same as that used earlier, but in this calculation, although a and S are the same, p is calculated for saturated water vapor at 2750 m above sea level for the following temperatures: 600° C, $p = 0.000161$ g/cm^3; 800° C, $p = 0.000135$ g/cm^3; and 1000° C, $p = 0.000114$ g/cm^3.

Substitution of the appropriate values in (1) indicates that the gases streamed past the fragment at the orifice at the following velocities at the temperature given: 177 m/sec at 600° C; 193 m/sec at 800° C; and 210 m/sec at 1000° C. The velocity was probably somewhat less, for some of the gases were denser than water vapor, and the fine ash particles must have increased the effective density.

Inasmuch as the fragment left the orifice at a velocity of 95 m/sec, this value must be added to the velocity of the gas past the fragment, giving the values: 272 m/sec at 600° C; 288 m/sec at 800° C; and 305 m/sec at 1000° C. As the diameter of the orifice was two meters, the volumes of the gases that would have left the vent at the above velocities were: 854 m^3/sec at 600° C; 904 m^3/sec at 800° C; and 958 m^3/sec at 1000° C.

According to the preceding values and the assumption that the gases were pure water vapor, the weights of the gases leaving the vent were as follows: 0.161 kg/m^3 at 600° C; 0.132 kg/m^3 at 800° C; and 0.114 kg/m^3 at 1000° C. The weight of water vapor leaving the vent per second was therefore: 0.14 met tons/sec at 600° C; 0.12 met tons/sec at 800° C; and 0.11 met tons/sec at 1000° C. Consequently, the daily weight of water vapor was: 11,900 met tons/day at 600° C; 10,500 met tons/day at 800° C; and 9400 met tons/day at 1000° C.

The weights of water vapor for the temperatures given are probably high, for the gases issuing from the vent were certainly not all water vapor; the error is probably offset somewhat, however, by the fact that the gases must have been at least a bit denser than indicated by the value used. Inasmuch as so many of the factors that enter into the calculations were not subject to direct measurement, and changes in the value of some of these factors would tend to cancel out changes in the value of other factors, the writer feels that the weights given above are reasonable for the temperatures given and are probably not far from reality.

Weight of water relative to weight of lava and pyroclastic material--As shown in Figure 6 and Table 6, the total weight of lava and pyroclastic material erupted daily at Parícutin in 1945, during the period for which the weight of water emitted from the crater was calculated, amounted to an average of about 1.2 million metric tons. The weight of water vapor issuing from the crater, assuming that the temperature of expulsion was 800° C, was estimated in the preceding chapter to have amounted to some 10,500 metric tons per day. This weight probably represents at least 80 pct of the water issuing from the crater and the hot flows. On this assumption, the weight of water would be increased to about 13,100 metric tons per day. To this should be added the water contained in the flows after solidification, which by assay are known to average about 0.1 pct H_2O. As the average daily lava emission in 1945 amounted to about 510,000 metric tons, some 510 tons of water was fixed daily by the lava. If this quantity is added to the weight of water from other sources, the total would amount to about 13,600 metric tons per day.

The percentage of water in the magma reaching the surface in 1945 was therefore about 1.1 pct on the average. The writer feels that this figure is not in error by more than a few tenths of one per

cent of the true water content of the magma that reached the surface in that year. Inasmuch as most igneous petrologists would accept a water content of this magnitude in basaltic magmas, there is no need to postulate that the rising lava column was greatly enriched by the introduction of ground waters; the juvenile water in gaseous form and other gases could well have accounted for all the explosive activity of Parícutin, at least during 1945. If the proportion of water to total solids had been nearly constant throughout the period of activity of the Volcano, the total weight of water expelled would have amounted to some 39 million metric tons--the approximate weight of a body of water about six kilometers square by one meter deep.

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J. WILLARD GIBBS' VECTOR ANALYSIS IN STRUCTURAL GEOLOGY

V. G. Gabriel and Harold L. Pierson

Abstract--A vector system is established in a hemisphere of a unit radius and certain pertinent relationships are derived for lines located in the same plane. Examples for the solution of field problems, commonly encountered in structural geology, and the use of the vector system are given.

Introduction--The application of stereographic projections and other types of projections, based on descriptive geometry, is widespread in structural geology. Although the use of those projections usually leads to rapid and relatively accurate graphical solutions, the application of a mathematical method, such as vector analysis, is justified in a case where a greater accuracy is desired.

The problem--Assume a right-hand vector coordinate system $\bar{i}, \bar{j}, \bar{k}$, with point O as the point of origin (see Fig. 1). Also assume that the vector system is confined to a hemisphere of unit radius. In plan view the hemisphere will be represented by a circle ESWN and in front view by a semicircle $EMWO_1$, where the lines ON, OE, O_1M are the positive directions of the vector coordinates $\bar{i}, \bar{j}, \bar{k}$, respectively.

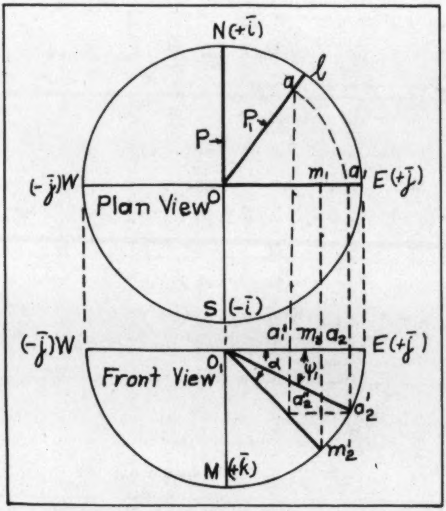

Fig. 1--Plan and front views of a unit hemisphere and planes P and P_1

Establishment of apparent and true dips relationship and other pertinent equations related to the same plane

First method--Assume that a plane, or a formation, whose angle of true dip is equal to α degrees, strikes along the line ON of $\bar{i}$ axis (Fig. 1). In the front-view projection, the true dip of the plane will be represented by an angle EO_1m_2' equal to the angle of α degrees. The length of the line O_1m_2' is equal to one and its projection on the plan view will be a line Om_1 equal to cos α (from the triangle $O_1m_2'm_2$). Assume that a vertical plane is passing through point O and cutting the horizontal plane ESWN, that is, the plane of the plan view, along a line $O\ell$, making an angle ℓOE equal to θ_1 degrees with the line OE, that is, the $\bar{j}$ coordinate axis. Assume the vertical plane intersects the formation under consideration along a line which is piercing the unit hemisphere at a point whose plan- and front-view projections are points a and a_2'', respectively. By rotating the line Oa until it coincides with the line OE and projecting the line Oa_1 equal to Oa on the semicircle of the front-view projection, we obtain a point a_2'. By connecting points O_1, a_2, and a_2' we obtain a triangle $a_2O_1a_2'$ where the angle of $a_2O_1a_2'$ is equal, let us say, to ψ_1 degrees. In structural geology this angle is referred to as the angle of the apparent dip in the $O\ell$ direction. The lines Om_2' and OA may be considered as the vectors $\bar{R}_1$ and $\bar{R}_2$ respectively, where the line OA is the line of intersection of the planes under consideration and point A is located on the unit hemisphere. The plan- and front-view projections of line OA are Oa and $a_1'a_2''$ respectively.

Vectorially it can be expressed

$$\left.\begin{aligned}\overline{O_1m_2'} &= \bar{R}_1 = x_1\bar{i} + y_1\bar{j} + z_1\bar{k}\\ \overline{OA} &= \bar{R}_2 = x_2\bar{i} + y_2\bar{j} + z_2\bar{k}\end{aligned}\right\}\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where $x_1, y_1, z_1, x_2, y_2, z_2$ are the scalar magnitudes.

But the equation of a sphere is

$$\bar{R} \bullet \bar{R} = \text{constant} \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $\bullet$ means a scalar product of two vectors.

From (2) we obtain for a unit hemisphere

$$\left.\begin{aligned}\bar{R}_1 \bullet \bar{R}_1 &= \text{constant} = 1\\ \bar{R}_2 \bullet \bar{R}_2 &= \text{constant} = 1\end{aligned}\right\}\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

But from triangles $O_1a_2a_2'$, Oaa_o, $O_1a_1'a_2''$ we have

$$Oa = Oa_1 = O_1a_2 = O_1a_2' \cos\psi_1 = 1 \times \cos\psi_1 \ldots\ldots\ldots \quad (4a)$$

$$aa_o = Oa \sin\theta_1 = \cos\psi_1 \sin\theta_1 = x_2 \ldots\ldots\ldots \quad (4b)$$

$$\begin{aligned}a_2a_2' = a_1'a_2'' = 0_1a_1' \tan\alpha = Oa_o \tan\alpha\\ = Oa \cos\theta_1 \tan\alpha = \cos\psi_1 \cos\theta_1 \tan\alpha = z_2\end{aligned} \ldots\ldots\ldots \quad (4c)$$

$$Oa_o = Oa \cos\theta_1 = \cos\psi_1 \cos\theta_1 = y_2 \ldots\ldots\ldots \quad (4d)$$

From triangle $O_1m_2m_2'$ we have

$$O_1m_2 = O_1m_2' \cos\alpha = 1 \times \cos\alpha = \cos\alpha = y_1 \ldots\ldots\ldots \quad (5a)$$

$$m_2m_2' = O_1m_2' \sin\alpha = 1 \times \sin\alpha = \sin\alpha = z_1 \ldots\ldots\ldots \quad (5b)$$

$$O = x_1 \ldots\ldots\ldots \quad (5c)$$

However, from (3)

$$\bar{R}_1 \bullet \bar{R}_1 = 1 = x_1^2 + y_1^2 + z_1^2 \ldots\ldots\ldots \quad (6a)$$

$$\bar{R}_2 \bullet \bar{R}_2 = 1 = x_2^2 + y_2^2 + z_2^2 \ldots\ldots\ldots \quad (6b)$$

and

$$x_1^2 + y_1^2 + z_1^2 = x_2^2 + y_2^2 + z_2^2 \qquad (7)$$

By substituting the values of $x_1, y_1, z_1, x_2, y_2, z_2$ from (4) and (5) into (7), we obtain

$$(\cos \psi_1 \sin \theta_1)^2 + (\cos \psi_1 \cos \theta_1)^2 + (\cos \psi_1 \cos \theta_1 \tan \alpha)^2 = \cos^2 \alpha + \sin^2 \alpha = 1 \qquad (8)$$

It was shown by GABRIEL and MILLER [1952, p. 737] that (8) is the equivalent of a well-known formula

$$\tan \psi = \tan \alpha \cos \theta \qquad (9)$$

where ψ is the angle of apparent dip, α is the angle of true dip, and θ is the horizontal angle between the apparent and true dips.

Second method--Assume that a plane P whose true strike is located along the line ON, that is, the $\bar{i}$ axis, has a true dip equal to α degrees east. In the plan view it will be represented by the lines ON (strike) and OE (the direction of the true dip); in front view the plane P will be represented by point O_1 and the line O_1m_2', respectively (Fig. 1).

A vertical plane P_1 passing through point O and the line $O\ell$ and whose apparent dip is equal to ψ_1 degrees will have the lines Oa and O_1a_2'' as its plan- and front-view projections, respectively.

Assume that the vector lines $\overline{ON}$ and $\overline{O_1m_2'}$, located in plane P, will be designated as vectors $\bar{R}_o$ and $\bar{R}_n$, respectively, or

$$\overline{ON} = \bar{R}_o = x_o\bar{i} + y_o\bar{j} + z_o\bar{k} = \bar{i} \qquad (10a)$$

$$\overline{O_1m_2'} = \bar{R}_n = x_n\bar{i} + y_n\bar{j} + z_n\bar{k} \qquad (10b)$$

where $x_o, y_o, z_o, x_n, y_n, z_n$ are the corresponding magnitudes of the vector components equal to

$$x_o = 1 \qquad x_n = 0 \qquad (11a)$$

$$y_o = 0 \qquad y_n = \cos \alpha \qquad (11b)$$

$$z_o = 0 \qquad z_n = \sin \alpha \qquad (11c)$$

where the equations for x_n, y_n, z_n were obtained from (5).

However, the intersection of the vertical plane P_1 with the plane P is a line OA whose plan- and front-view projections are line Oa and O_1a_2'', respectively. By designating the vector line $\overline{OA}$ by a vector $\bar{R}\,\psi_1$, we obtain

$$\overline{OA} = \bar{R}\,\psi_1 = x_1\bar{i} + y_1\bar{j} + z_1\bar{k} \qquad (12)$$

where from (4) the axial components are

$$\left.\begin{matrix} x_1 = \cos \psi_1 \sin \theta_1 & y_1 = \cos \psi_1 \cos \theta_1 \\ z_1 = \cos \psi_1 \cos \theta_1 \tan \alpha & \end{matrix}\right\} \qquad (13)$$

By substitution into (10) and (12) instead of $x_o, y_o, \ldots . z_n$, their magnitudes expressed in ψ_1, θ_1, α we obtain

$$\bar{R}_o = \bar{i} \qquad (14a)$$

$$\bar{R}_n = \cos \alpha \bar{j} + \sin \alpha \bar{k} \qquad (14b)$$

$$R\,\psi_1 = (\cos \psi_1 \sin \theta_1)\, i + (\cos \psi_1 \cos \theta_1)\, j + \sin \psi_1 k \qquad (14c)$$

Any vector located in the plane of the formation under consideration and drawn from point O can be expressed through the vectors $\bar{R}_o$ and $\bar{R}_n$ as

$$\overline{R}\,\psi_1 = S_1\,\overline{R}_o + t_1\overline{R}_n \tag{15}$$

where s_1 and t_1 are the scalar quantities.

By substitution from (14) into (15), we obtain

$$\overline{R}\,\psi_1 = (\cos\psi_1 \sin\theta_1)\,\overline{i} + (\cos\psi_1 \cos\theta_1)\,\overline{j} + \sin\psi_1\overline{k} = (S_1)\,\overline{i} + (t_1 \cos\alpha)\,\overline{j} + (t_1 \sin\alpha)\,\overline{k} \tag{16}$$

By equating the corresponding components on both sides of (16) we have

$$\cos\psi_1 \sin\theta_1 = s_1 \tag{17a}$$

$$\cos\psi_1 \cos\theta_1 = t_1 \cos\alpha \tag{17b}$$

$$\sin\psi_1 = t_1 \sin\alpha \tag{17c}$$

By dividing (17c) by (17b)

$$\sin\psi_1/\cos\psi_1 \cos\theta_1 = t_1 \sin\alpha/t_1 \cos\alpha = \tan\alpha \tag{18}$$

By transposing, we obtain from (18)

$$\sin\psi_1/\cos\psi_1 = \tan\psi_1 = \cos\theta_1 \tan\alpha \tag{19}$$

where ψ_1 and α are the angles of apparent and true dips, respectively, and θ_1 is the angle between the directions of the apparent and true dips.

From (17) the following pertinent relationship can be derived for unit vectors drawn from point O and located in the same plane passing through point O

$$\left.\begin{array}{l} \cos\psi_1 \sin\theta_1 = S_1 \\ \cos\psi_2 \sin\theta_2 = S_2 \\ \cdots\cdots\cdots\cdots \\ \cos\psi_n \sin\theta_n = S_n \end{array}\right\} \tag{20a}$$

$$\left.\begin{array}{l} t_1 = \cos\psi_1 \cos\theta_1/\cos\alpha \\ \cdots\cdots\cdots\cdots \\ t_n = \cos\psi_n \cos\theta_n/\cos\alpha \end{array}\right\} \tag{20b}$$

$$\left.\begin{array}{l} t_1 = \sin\psi_1/\sin\alpha \\ \cdots\cdots\cdots\cdots \\ t_n = \sin\psi_n/\sin\alpha \end{array}\right\} \tag{20c}$$

where $t_1, t_2, \ldots t_n, s_1, s_2, \ldots s_n$, are the scalar quantities; $\psi_1, \psi_2, \ldots \psi_n$, are the angles of apparent dips; $\theta_1, \theta_2, \ldots \theta_n$, are the angles between the directions of true and apparent dips. The true dip of the formation under consideration is the angle α.

By taking the scalar products of both sides of (15) we have

$$\overline{R\psi_1} \bullet \overline{R\psi_1} = 1 = (s_1\overline{R}_o + t_1\overline{R}_n) \bullet (s_1\overline{R}_o + t_1\overline{R}_n) = s_1\overline{R}_o \bullet s_1\overline{R}_o + s_1t_1\overline{R}_n \bullet \overline{R}_o + s_1t_1\overline{R}_o \bullet \overline{R}_n + t_1\overline{R}_n \bullet t_1\overline{R}_n = s_1^2(1.1)\cos 0^\circ + (1.1)\cos 90^\circ + t_1^2(1.1)\cos 0^\circ = s_1^2 + 0 + t_1^2 \text{ or } 1 = s_1^2 + t_1^2 \tag{21}$$

Similarly, from (21) for all unit vectors located in the same plane and starting from point O

$$\left.\begin{array}{l} 1 = s_1^2 + t_1^2 \\ 1 = s_2^2 + t_2^2 \\ \cdots\cdots\cdots \\ 1 = s_n^2 + t_n^2 \end{array}\right\} \qquad (22a)$$

$$s_1^2 + t_1^2 = s_2^2 + t_2^2 = s_3^2 + t_3^2 = \ldots\ldots = s_n^2 + t_n^2 \qquad (22b)$$

Vectorial relationship of planes different in true strikes and true dips

Assume that in addition to plane P, whose true dip is α degrees east and whose true strike is the line ON, we have a second plane P_2 (whose true strike is the line Od and the true dip is equal to β degrees east (see Fig. 2) located in a vertical plane passing through On_1 of the plan view).

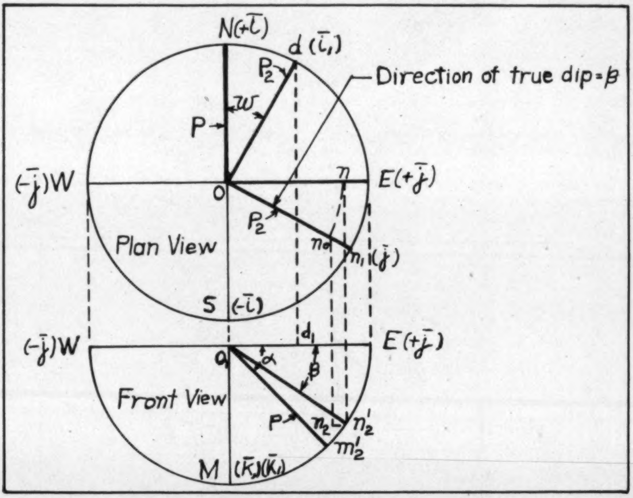

Fig. 2--Plan and front views of planes P and P_2 whose angles of true dips are equal to α and β degrees, respectively

In the front view the lines O_1d_1 and O_1n_2 are the strike and dip projections, respectively, where the points n_o and n_2 are the projections of a line located in the plane P_2 and piercing the unit hemisphere at point N_1. By assuming a new coordinate system $\bar{i}_1$ (line Od), $\bar{j}_1$ (line On_1), and $\bar{k}_1$ (line O_1M) and designating

$$\overline{Od_1} = \overline{R_{o1}} \qquad (23a)$$

$$\overline{ON_1} = \overline{R_{n1}} \qquad (23b)$$

$$\overline{O_1M} = \overline{k_1} = \bar{k} \qquad (23c)$$

where the lines On_o and O_1n_2 are the projections of the line ON_1.

From (14) and (23) we obtain

$$\overline{R}_{o1} = \overline{i}_1 \tag{24a}$$

$$\overline{O_1N_1} = \overline{R}_{n1} = \cos\beta j_1 + \sin\beta k_1 \tag{24b}$$

$$\overline{O_1M} = \overline{k}_1 = \overline{k} \tag{24c}$$

By expressing the vectorial coordinates $\overline{i}_1$, $\overline{j}_1$, $\overline{k}_1$, in terms of $\overline{i}$, $\overline{j}$, $\overline{k}$, we obtain from (24)

$$\overline{R}_{o1} = (\cos\omega)\,\overline{i} + (\sin\omega)\,\overline{j} \tag{25a}$$

$$R_{n1} = \cos\beta(\cos\omega\overline{j} - \sin\omega\overline{i}) + \sin\beta\,\overline{k} \tag{25b}$$

where ω is the angle between the directions of the true strikes of planes P and P_2.

From (25) we have

$$\overline{R}_{o1} = (\cos\omega)\,\overline{i} + (\sin\omega)\,\overline{j} \tag{26a}$$

$$R_{n1} = -\sin\omega\cos\beta\,\overline{i} + \cos\omega\cos\beta\,\overline{j} + \sin\beta\,\overline{k} \tag{26b}$$

Application of vector analysis for the solution of problems

Problem--Find the true dip and strike of a formation whose apparent strikes are N 55° E and N 85° E, and whose apparent dips are 32° E and 45° E, respectively.

In the solution, assume that the $\overline{i}_1$, $\overline{j}_1$, $\overline{k}_1$ vectorial system is oriented in such a way that the $\overline{i}_1$ axis coincides with the true strike and the $\overline{j}_1$ axis with the direction of true dip of the formation.

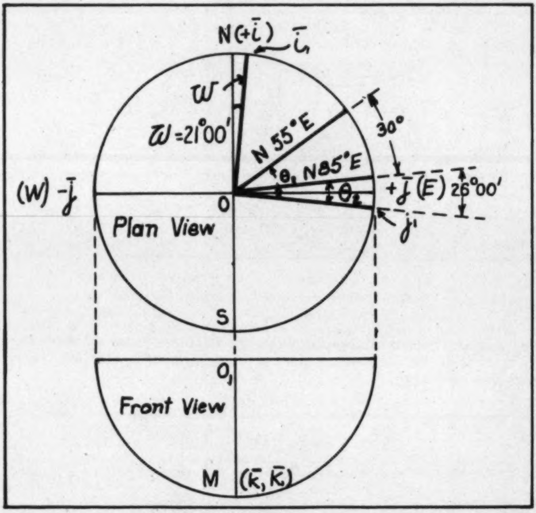

Fig. 3--Plan and front views for solution of problem

From (14), we can write

$$\bar{R}_{o1} = \bar{i}_1 \tag{27a}$$

$$\bar{R}_{n1} = \cos\ \alpha \bar{j}_1 + \sin\ \alpha \bar{k} \tag{27b}$$

where $\bar{R}_{o1}$ = unit vector of the strike line and $\bar{R}_{n1}$ = unit vector of the line lying both in the formation and in the vertical plane passing through the direction of the true dip equal to α degrees.

Assume also the new vectorial system $\bar{i}$, $\bar{j}$, $\bar{k}$, is established with the $\bar{i}$ axis striking in the north-south direction along line ON (see Fig. 3), where the angle ω is the angle between the $\bar{i}$ and $\bar{i}_1$ coordinate axes. From (26b) we have

$$\bar{R}_{o1} = \cos\ \omega \bar{i} + \sin\ \omega \bar{j} \tag{28a}$$

$$\bar{R}_{n1} = -\sin\ \omega \cos\ \alpha \bar{i} + \cos\ \omega \cos\ \alpha \bar{j} + \sin\ \alpha \bar{k} \tag{28b}$$

However, from (19) we have

$$\tan\ \psi_1 = \cos\ \theta_1 \tan\ \alpha \tag{29a}$$

$$\tan\ \psi_2 = \cos\ \theta_2 \tan\ \alpha \tag{29b}$$

where

$$\theta_1 - \theta_2 = 85° - 55° = 30° \tag{30}$$

or from (30)

$$\theta_1 = 30° + \theta_2 \tag{31}$$

By dividing (29a) by (29b) and by substituting from (31), we obtain

$$\frac{\tan\ \psi_1}{\tan\ \psi_2} = \frac{\cos\ \theta_1 \tan\ \alpha}{\cos\ \theta_2 \tan\ \alpha} = \frac{\cos\ \theta_1}{\cos\ \theta_2} = \frac{\cos\ (30° + \theta_2)}{\cos\ \theta_2} = \frac{\cos 30°\ \cos\ \theta_2 - \sin\ 30°\ \sin\ \theta_2}{\cos\ \theta_2}$$

$$= \cos\ 30° - \sin\ 30°\ \tan\ \theta_2 = 0.86603 - 0.5\ \tan\ \theta_2 \tag{32}$$

By substituting the values of ψ_1 and ψ_2 into (32), we obtain

$$\tan\ 32°/\tan\ 45° = 0.86603 - 0.5\ \tan\ \theta_2 \tag{33}$$

From (33)

$$0.5\ \tan\ \theta_2 = 0.86603 - \tan\ 32°/\tan\ 45° \tag{34}$$

but

$$\tan\ 32°/\tan\ 45° = 0.62487 \tag{35}$$

By substituting into (34) the ratio of the tangents from (35), we have

$$\tan\ \theta_2 = 0.86603/0.5 - 0.62487/0.5 = 0.4823 \tag{36a}$$

and

$$\theta_2 = 26°\ 00' \tag{36b}$$

Therefore, from (31) we have

$$\theta_1 = 30° + \theta_2 = 30° + 26° = 56° \tag{37a}$$

$$90° - 56° = 34°\ \text{(angle between the } \bar{i}_1 \text{ axis and N 55° E line)} \tag{37b}$$

but

$$55° - 34° = 21°\ 00' \tag{38}$$

By substituting into (29b) the corresponding magnitude from (36), we obtain

$$\tan \psi_2 = \tan 45^\circ = 1 = \cos 26^\circ \tan \alpha = 0.89879 \tan \alpha \qquad (39)$$

or from (39)

$$1/0.89879 = \tan \alpha \quad \text{or} \quad \alpha = 48^\circ \text{ (approx.)} \qquad (40)$$

By substituting into (28) the corresponding magnitudes from (38) and (40), we have

$$\overline{R}_{o1} = \cos 21^\circ \,\overline{i} + \sin 21^\circ \,\overline{j} \qquad (41a)$$

$$\overline{R}_{n1} = - \sin 21^\circ \cos 48^\circ \,\overline{i} + \cos 21^\circ \cos 48^\circ \,\overline{j} + \sin 48^\circ \,\overline{k} \qquad (41b)$$

Summary and conclusions

J. Willard Gibbs' vectorial system is established in a unit hemisphere and pertinent relationship between apparent and true dips is derived. Later certain relationship is established between the lines drawn in the same plane.

It is probable that for certain types of problems related to mining geology a vectorial system established in an infinite space should be used.

It is probable that the preliminary plotting of vector cosine and sine curves on the plan and side views of a unit hemisphere, somewhat similar to the method employed by Gabriel and Sobie, would greatly expedite the solution of the vectorial problems.

Acknowledgment--We would like to express our thanks to A. C. Spreng of the Missouri School of Mines and Metallurgy, University of Missouri, Rolla, Missouri, for his helpful suggestions; and Charlene Faulkner, for checking and typing the manuscript.

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Transactions, American Geophysical Union Volume 34, Number 4 August 1953

REPORT OF THE COMMITTEE ON EVAPORATION AND TRANSPIRATION, 1951-1952

A. R. Croft, Chairman

1952	1953	1954
Henry W. Anderson	J. M. Aikman	R. H. Burgy
Robert W. Gerdel	Harry F. Blaney	E. G. Dunford
C. W. Thornthwaite	Carl Rohwer	Richard B. Marston

The Committee's report for 1951-52 consists of items dealing with evapotranspiration as influenced by soil-plant-climatic interaction and with methods of determining water loss.

R. W. Gerdel (Corps of Engineers, U. S. Army, Wilmette, Ill.)--The Snow, Ice, and Permafrost Research Establishment is highly interested in a little recognized evaporation problem in snow-covered areas. This is the "production of depth hoar within the snow blanket." Investigations at Fort Churchill, Manitoba, and adjacent areas in the Arctic in February and March, 1951, indicate that the production of massive amounts of depth hoar is the result of a soil-plant-climate interaction. Depth hoar may consist of a few inches to several feet of a loose, fragile horizon of crystals which have little or no resemblance to the more classic forms of snow crystals. The depth hoar crystals lack cohesiveness, and when such horizons exist near the snow surface, the supporting capacity for troops, vehicles, and planes is greatly reduced. This very deceptive hazard is difficult to recognize.

It appears that the dense, short vegetation on the Arctic tundra may reduce thermal contact between the snow blanket and the soil beneath. With snow surface temperatures of -40°F, a steep temperature gradient is set up between the soil and the snow within the air spaces created by the tundra vegetation. Low-temperature evaporation or sublimation processes are induced within the air pockets which cause the precipitation of a hoar-frost type of crystal on the lower surface of the supported snow blanket, and on the vegetation itself much as hoar frost is accumulated on the branches of trees on very cold nights when clear skies prevail in snow-covered areas.

Having once been established, the process appears to be a continuing one and a large portion of the snow blanket may undergo such sublimative metamorphosis. At Fort Churchill horizons of such depth hoar are in excess of one foot in thickness with less than a foot of normal snow overlying them.

The production of depth hoar is recognized as a major cause of avalanches in the Alps. It is only recently that it has been recognized as a problem in the Arctic and Subarctic, and only in this area has it been observably associated with vegetation. The plant association, of course, is not a transpirational type such as is usually associated with water losses from forest, range, and cultivated lands. The greatest thickness of depth hoar, however, is in tundra-covered areas and the least where the snow mantle lies over bare rock.

Intensive studies now supported by this Establishment on the microclimatic regime over a snow surface at the Central Sierra Snow Laboratory will be extended to areas where the depth hoar phenomenon can be investigated.

Oliver Kehrlein and W. T. Wilson (Sierra Club and U. S. Weather Bur., respectively)--Experiments were set up to test F. E. Matthes' theory that almost all snow ablation over 12,000 ft is by evaporation rather than runoff. On Bishop Creek drainage in California at 12,100 ft 99 pct of the snow ablation was recovered as runoff. From snow blocks of known volume and water equivalent, water yield was 97.3 pct.

In a paper presented before the American Society of Civil Engineers at their New York meetings in October, 1951, W. T. Wilson reports on some evaporation experiments conducted on Mt. Whitney which show evaporative losses from snow at 14,000 ft to be a very small fraction of the melting which occurred. Vapor losses were not so much from the actual snow as from the moist soil and water pools fed by the melting snow.

Harry F. Blaney (Soil Conservation Service, Los Angeles, California)--Measurements of monthly evaporation, transpiration, and evapotranspiration (consumptive use) have been made by members of the research staff, Soil Conservation Service, at various times in recent years in several irrigated areas in western United States. These measurements of evapotranspiration under each of the physical and climatical conditions of large areas are expensive and time-consuming. A rapid method [Determining evapotranspiration by phreatophytes from climatological data, Trans. Amer. Geophys. Union, v. 33, pp. 61-66, 1952] of transposing the results of measurements to areas of similar conditions but where such data are lacking is now being used by the Nevada, Wyoming, Oregon, and other agricultural experiment stations.

Table 1--Examples of computed normal monthly evapotranspiration by irrigated crops

Month	Alfalfa[a]	Cotton[b]	Grapefruit[c]	Pasture (grass)[d]	Pasture (grass)[e]	Peaches[f]
	inch	inch	inch	inch	inch	inch
April	3.6	3.4	3.8	3.5	2.9	2.5
May	5.1	4.3	4.7	4.5	4.0	3.3
June	6.1	4.7	5.7	5.0	4.7	3.8
July	7.7	4.9	6.2	5.7	5.1	4.2
August	7.2	4.7	6.2	5.3	4.6	3.8
September	5.2	3.8	5.2	4.2	3.6	3.0
October	3.5	3.1	3.9	3.3	2.7	2.3

[a] Antelope Valley, California. [b] Carlsbad, New Mexico. [c] Phoenix, Arizona. [d] Charleston, South Carolina. [e] Northampton, Massachusetts. [f] Hagerstown, Maryland.

Examples of the computed monthly evapotranspiration data for some common crop plants are shown in Table 1. The application of the procedure provides a means of obtaining consumptive use data, in planning multiple-use water conservation projects, at a great saving in time and money.

John R. Mather (Johns Hopkins University, Laboratory of Climatology, Seabrook, New Jersey)--Preliminary investigations at Seabrook indicate that soil-moisture content for optimum growth may be above field capacity rather than below, as has been commonly accepted.

Investigators have long believed that above field capacity, mesophytic and xerophtic plants had all the water they could use and that the relation between increasing soil moisture, transpiration, and growth would disappear. Such a tentative conclusion was also reached at Seabrook during 1950 on the basis of limited field tank observations and was mentioned in the Report of the Committee on Evaporation and Transpiration, 1950-51 [Trans. Amer. Geophys. Union, v. 33, p. 121, 1952]. Since that time there has been reason to doubt the complete validity of that conclusion which was based on measurements in six irrigated field tanks. The problem was studied further in 1951, of which the following is a progress report.

The field tanks and an area around the tanks are covered with a blue grass and clover mixture kept cut to a height of about ten cm. At present, seven evapotranspirometers (field tanks lettered A - G) are installed at the experimental site. Tanks A - F are four square meters in surface area and 70 cm deep. Tank G has a surface area of 0.25 sq m and a depth of 50 cm. Although the crop and cultivation practices are the same on all the evapotranspirometers, the watering regimes differ. Tanks A through E have permanent water tables: 55 cm depth in Tanks, B, C, and E, and 35 cm depth in tanks A and D. Tanks F and G have no permanent water table but are watered daily by sprinkling just enough to insure a small amount of daily percolation from the field tank. Thus the soil in these tanks for a time each day contains water considerably above field-moisture capacity. The water use, moisture tension, and plant growth data for the period July 10 to September 30, 1951, are summed in Table 2.

Vegetation in tanks F and G, with soil above field capacity, consumed on the average about 25 pct more than vegetation in the tanks with soil below field capacity. The heavily watered plants produced also from about two to three times more vegetation (green weight) than plants grown in soil below field capacity. Moisture tension in tank F was only about 64 pct of that in tanks A and D and 40 pct of B, C, and E, indicating much less resistance to uptake of water by plants grown in soil above field capacity. This doubtless was a principal factor in the greater consumptive use and growth of vegetation in tanks with soil above field capacity. On the basis of the 1951 studies, no actual optimum value of soil-moisture content could be determined. It is expected that the investigation will be expanded into 1952 to study this and related factors.

Table 2--Data on evapotranspirometers, July 10-September 30, 1951

Tanks	Water added	Water collected	Evapotranspiration	Soil moisture tension at 15 cm depth	Fresh cut weight of vegetation
	mm	mm	mm	mb	lb/sq m
Average tanks B, C, E (water 55 cm)	392	106	286	76	1.08
Average tanks A, D (water 35 cm)	368	82	286	48	1.02
Tank F	673	317	356	30	3.10
Tank G	807	400	407	. .[a]	4.06

[a] No tensiometer installed.

A. R. Croft (U. S. Forest Service, Ogden, Utah)--In a recent study to determine the effect of different plant-cover types in situ on water available for streamflow, summer evapotranspiration was evaluated on the basis of the following formula in which all values are water depth in inches

$$L = (W_1 - W_2) + (P - R)$$

in which L is evapotranspiration; W_1 , field-moisture capacity of soil; W_2, soil moisture at end of growing season; P, rainfall measured at ground surface; R, surface runoff.

In the current study, plots as large as 1/10 acre were used and moisture losses determined to a depth of six feet in increments of one foot. Sampling points were selected at random on each sampling date. Per cent soil moisture and apparent specific gravity were determined at foot depths on soil samples obtained with a long sampling tube (Geotome), from which water volume (depth-inches) was calculated.

A paper reporting results of a study of evapotranspiration and water yield from three cover types under natural conditions has been approved for publication in the Transactions. The net reduction in soil moisture in the six-foot deep mantle during the June-September growing season was about 12 inches from an aspen-herbaceous type, eight inches from a herbaceous type, and four inches from bare soil made by removal of aspen trees, herbaceous plants, and litter.

Intermountain Forest and Range Experiment Station (A. R. C.),
Ogden, Utah

(Manuscript received January 5, 1953; presented by title at the Thirty-Third Annual Meeting, Washington, D. C., May 6, 1952; open for formal discussion until January 1, 1954.)

Transactions, American Geophysical Union   Volume 34, Number 4   August 1953

DISCUSSION OF

"AREA-DEPTH STUDIES FOR THUNDERSTORM RAINFALL IN ILLINOIS"

by F. A. HUFF and G. E. STOUT

[Trans., v. 33, pp. 495-498, 1952]

Ven Te Chow (Department of Civil Engineering, University of Illinois, Urbana, Illinois)--In the science of hydrometeorology, many attempts have been made to investigate the areal-depth relationship of rainfall, but little information has been obtained sufficiently to draw positive conclusions, particularly in connection with storms occurring in small watersheds. The writer is glad to see that this paper supplies the valuable information, resulting from area-depth studies of rainfall, that maximum rainfall data for thunderstorm rainfall in small basins bear a linear relationship to the square root of area. As this relationship is expressible by a simple and workable equation, it is indeed very useful for many engineering purposes.

In connection with one of the research projects on hydrologic studies at the University of Illinois, the writer has studied the areal distribution of storm rainfalls over a small watershed which is the same basin of 5.2 sq mi as mentioned in the paper. The results of his study on 31 major storms may be converted to the per cent of depth to the square root of area relationship as shown in Figure 8 [CHOW, 1952, Fig. 9]. For the sake of comparison, the relationship based on a design curve for the same basin, developed independently by HORNER and SHIFRIN [1949], consulting engineers of St. Louis, Missouri, is also presented in Figure 8. Both curves verify satisfactorily the straight-line relationship revealed in this paper.

The writer has also approached this problem from a theoretical angle. He assumed that any observed storm pile, as shown in Figure 9a, may be converted into one, as shown in Figure 9b, which has circular horizontal sections, symmetrical with respect to the vertical axis of the pile. The so-called storm pile is simply a three-dimensional representation of the rainfall isohyetals. It may be seen that the converted symmetrical storm pile can be produced by revolving the curve PO at a complete circle about the vertical Y-axis. The curve PO is the right-side intersection of the storm pile with the XY-plane (see Fig. 10).

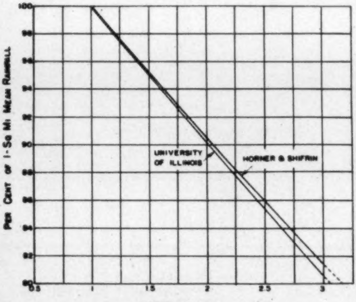

Fig. 8--Area-depth relations for Boneyard Watershed, Ill.

Let the curve PO be expressed by a polynomial

$$y = A + Bx + Cx^2 + Dx^3 + Ex^4 + \dots \quad (1)$$

in which x is the radius of a circular isohyetal. Then

$$dy = (B + 2Cx + 3Dx^2 + 4Ex^3 + \dots)\, dx \quad (2)$$

The average rainfall depth on the circular area X of radius x_o in Figure 10 is

$$Y = \left(y_o X + \int_{y_o}^{y_{max}} \pi x^2 dy\right)/X \quad (3)$$

Substituting (1) and (2) into (3) and noting that $y = y_o$ when $x = x_o$ and $X = \pi x_o^2$ or $x_o = X^{1/2}/\sqrt{\pi}$, (3) may be simplified as follows

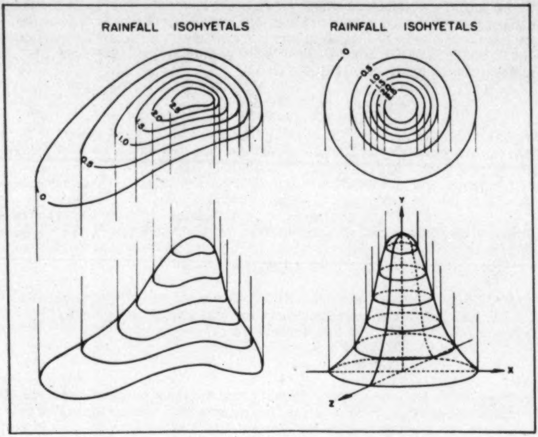
RAINFALL ISOHYETALS
RAINFALL ISOHYETALS
0
0.5
1.0
1.5
2.0
2.5
Y
X
Z

Fig. 9--Conversion of storm pile

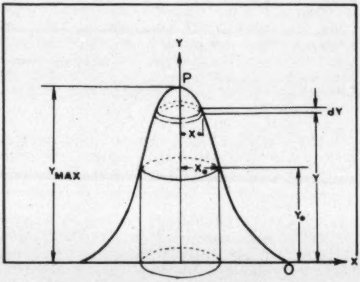
Y
P
dY
X
X_o
Y_{MAX}
Y
Y_o
O
X

Fig. 10--Analysis of storm pile

$$Y = A + Bx_o + Cx_o^2 + Dx_o^3 + Ex_o^4 + \dots + (1/x_o^2)\int_{x_o}^{0} x^2\,(B + 2Cx + 3Dx^2 + 4Ex^3 + \dots)\,dx$$

$$= A + (2B/3)\,x_o + (C/2)\,x_o^2 + (2D/5)\,x_o^3 + (E/3)\,x_o^4 + \dots$$

$$= a + bX^{1/2} + cX + dX^{3/2} + eX^2 + \dots \qquad (4)$$

in which a, b, c, d, e, ... are new coefficients. Eq. (4) should be the theoretical general equation of rainfall depth-area distribution for all types of storms.

As the area-depth studies for thunderstorm rainfall in small watersheds indicate that (4) is linear, the coefficients for higher orders of X, that is, c, d, e, ... in (4) or C, D, E, ... in (1), are nil. In other words, (1) becomes linear, or the curve PO is a straight line. It means that the storm pile of local thunderstorms should be very close to the form of a cone. Terms of higher orders of X in (4) must be considered when the straight-line relationship of the depth plotted against the square root of the area does not apply to storms covering larger areas, say more than 300 sq mi. It should be very interesting to see how many terms of X in (4) must be taken into account and how the equation fits for those storms studied by CORPS OF ENGINEERS [1945], which storms cover areas up to about 200,000 sq mi.

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DISCUSSION OF

"A RIGOROUS, SIMPLE METHOD OF MEASURING AND RECORDING PARTICLE-SIZE DISTRIBUTION IN DISPERSED MATERIAL"

by M. RIM

[Trans., v. 33, pp. 423-426, 1952]

Irving Sherman (U. S. Forest Service, Arcadia, Calif., received September 30, 1952)--The apparatus described in the original paper is indeed simple and interesting. However, it appears to have some disadvantages which are herewith considered, along with some suggestions for improvement.

As a type of sedimentation balance, the apparatus described records what is known as an Odén curve [KRUMBEIN and PETTIJOHN, 1938, pp. 112-117]. For most purposes this is not immediately useful. It is usually the practice to obtain from the Odén curve a graph in which particle sizes are plotted against cumulative percentages finer (or coarser). This involves drawing tangents to the Odén curve and noting their intercepts on the ordinate which indicates the mass of material settled. Drawing these tangents unavoidably involves the personal element and some inaccuracy. It is questioned whether the theoretical rigor of the apparatus described may not be largely offset by this consideration in comparison with those techniques which yield the cumulative percentage curve directly.

A question is also raised concerning the time required to interpret the record which involves at least several hundred glass and steel beads. Particularly where large numbers of samples must be analyzed quickly, it would seem highly preferable to record the results (for example) by some device such as an electrical strain gage and automatic graph recorder.

It is not clear to this writer why the solution surrounding the sedimentation tube should be more concentrated than that within, as indicated in Figure 1. Gravitational stability could be assured by the use of a sufficiently large air bubble at the top of the sedimentation tube; the solution could then be equally concentrated within and outside of the tube and thus eliminate the possibility of effects of molecular diffusion between two solutions of unequal concentration.

Apparently the author selected sodium hydroxide (NaOH) solution because he felt it to be a desirable dispersing agent for soils and similar materials. It is suggested that sodium hexametaphosphate [$(NaPO_3)_6$], which is now coming into ever-increasing acceptance, is much superior for this purpose [TYNER, 1939]. In his own work this writer has found it advisable to limit the dispersing agent concentration to a maximum of 0.005 normal in the sedimentation cylinder when the suspended material was about one per cent of the total suspension by weight. Higher concentrations appeared to give less dispersion than did this maximum. These comments about dispersing agents of course do not reflect upon the sedimentation apparatus itself.

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Pin-Nam Lin (Department of Civil Engineering, Colorado A. and M. College, Fort Collins, Colo., received Nov. 3, 1952)--The author is to be congratulated for presenting an instrument built of easily available parts. An instrument of this type, when perfected, would conceivably prove valuable in many problems. As it stands, it should be emphasized, however, that the new instrument cannot very well handle materials of wide range of size variation because the feed of glass beads is to be kept at a constant rate. During the earlier stage of a run, when the coarse portion of the sample is settling, the feed might be too slow to preserve the equilibrium of the float; yet, during the later stage, when the finer portion is settling, the same rate of feed might become too high. Moreover, since the same sedimentation tube has to be used throughout a single test, particles of all sizes must settle through the same height. This might mean an unduly long time required to complete a run, when the non-uniform sample contains very fine particles, whereas in the bottom-withdrawal tube or manometric methods the height of suspension is or can be reduced as the test goes on.

In the writer's opinion, none of the generally known hydraulic methods for size analysis of fine materials, including the author's method, could be truly rigorous, without having the problem of concentration completely solved. Study with uniform particles settling in a container has shown that the reduction in fall velocity could be as high as 20 pct of the single-particle fall velocity when the concentration is only one per cent by dry weight [LIN, 1951; McNOWN and LIN, 1952]. In the case of non-uniform particles, only when the suspension is gradually stratified can the effect of hydrodynamic interference on the fall velocity of a particle be calculated [LIN, 1951].

As to the matter of disturbance due to the interchange of liquid between the sedimentation tube and the measuring element, attention is called to the fact that there are already methods capable of reducing this to a minimum. For instance, in manometric methods of size analysis, if the measuring element is a differential manometer of the fixed interface type, such as the Wahlen gage [SKIDMORE, 1948], there should be very little interchange of liquid between the sedimentation tube and the manometer. In fact, when properly operated, there may be even less interchange of liquid than that which might take place in the bellow system mentioned by the author. Nevertheless, the interchange of liquid in a well-proportioned instrument operating at small concentrations is generally of minor importance. It is often the introduction of sample or the initial dispersion of the sample in the process of creating a suspension that creates considerable turbulence and even persistent density currents. Indeed, the writer would not be surprised if one should find the creation of a good suspension of a required type to be a baffling problem in the construction of a good instrument. From this viewpoint, it will be of interest to know how the sample is introduced and dispersed in the new instrument, initially how homogeneous is the suspension, and how is the sedimentation tube introduced into the bath without loss of solution from the tube and also without causing objectionable mixing to take place. Obviously, the height of the sedimentation tube will limit the largest size that can be analyzed, and the method of operating the instrument in turn limits the height of the tube which can be used.

Size distribution curves for a given sample tested by various well-known methods [U. S. GOVERNMENT and IOWA INSTITUTE OF HYDRAULIC RESEARCH, 1941, 1943], as well as the author's method, will be most interesting.

References

LIN, P. N., Effect of spacing and size distribution on the fall velocity of sediment, Ph.D. dissertation, University of Iowa, August, 1951.

McNOWN, J. S., and P. N. LIN, Particle concentration and fall velocity, Second Midwestern Conference on Fluid Dynamics, Ohio State University, 1952.

SKIDMORE, H. J., Development of a stratified-suspension technique for size-frequency analysis, Ph.D. dissertation, University of Iowa, 1948.

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M. Rim (Soil Science Dept., The Hebrew University, Jerusalem, Israel, Author's closure)--As the discussers have not brought up any identical or similar points in their many-sided comments, the author will answer them separately referring to the questions in the same order as they were posed.

Sherman's concern, that attained experimental accuracy may have to be sacrificed in the course of subsequent mathematical transformations involving differential operations, is not justified. His remarks might apply for non-continuous methods rendering data in terms of discrete, arbitrarily defined particle-size classes, whereas the method presented gives practically continuous curves that are differentiable at every point without involving ambiguity or the personal element. Moreover, the apparatus described yields directly sediment accumulation rate (represented by the number of glass beads missing in a given length of record tube or, inversely, by the distance between two missing beads in the tube), which is already the first differential of the Odén curve mentioned. As a consequence, the curves mentioned in Sherman's discussion are directly obtainable from bead records without having recourse to the lengthy graphical construction methods referred to by him. A quick way to obtain the graphs requested, making the suggested automatic graph-recorder unnecessary and having the advantage of rendering directly the curves on the customary log-of-size abscissa scale, is as follows:

A logarithmic scale is placed alongside the record tube so that readings, s_n, may be taken at all those points where glass beads are missing in the tube. If the units of the logarithmic scale are chosen such that

$$s = (1/2) \log_e [18 \eta fbh/(\rho_1 - \rho_2) g \ell]$$

then $s = \log_e d$, where ℓ denotes the geometric distance between a marking, s, and a reference point, S, on the scale (the scale being applied to the record tube in such a way that S corresponds to the tube's closed end), f is the feed rate of glass beads, b the average bead width, h the height of the apparatus' sedimentation tube, the remaining symbols standing for the familiar constants of Stokes' law and d for the Stokesian particle diameter. Thus the s_n-values indicate particle size directly; they are plotted, reading them from the record tube scale one after another in successive order, on the abscissa of ordinary graph paper. Between the successive readings the scale is moved backwards by one bead length to compensate for the width of the missing glass bead. The one-dimensional s_n-plot obtained constitutes the basis for all curves, serving immediately as their abscissa:

(1) A size-frequency integral curve is obtained by plotting for each point s_n an ordinate $y_n = |1/(s_{n+1} - s_{n-1})|$, where s_{n+1} and s_{n-1} refer to the points immediately preceding and succeeding s_n. The y_n-values are easily obtained by sliding a rule with a reciprocal scale along the abscissa; while applying the rule's end point to a point s_{n+1}, the value of y_n is read on the reciprocal scale at s_{n-1}.

(2) A cumulative curve (indicating content finer directly in percentages if the sample analyzed weighs exactly 100 glass beads, proportional units otherwise) results when the ordinates, y_n, obtained as previously, are increased by serial numbers, n, in such a way that the ordinate of the point farthest to the left has one graph unit added to it, the next one two, and so on. The ordinate of this curve is then $z_n = y_n + n$. (A plot of n by itself against s_n renders an Odén- or Wiegner-type curve.)

Sherman's suggestion with reference to an alternative way of maintaining gravitational stability in the sedimentation tube cannot be accepted. If the density of the liquid surrounding the sedimentation tube were not as high as the bulk density of the suspension inside, pockets of clear liquid might tend to enter the sedimentation tube from below and rise within it, by force of their lesser bulk density, right to the top. The mere possibility of such an occurrence would label the method as non-rigorous and the results obtained as unreliable. The failure to guarantee gravitational stability in the settling suspensions was, historically, what led to the rejection of the classical elaborate sedimentation balances of Odén, Keen, and later workers, as well as of Wiegner's and other methods that necessitate open manometer connections in the sedimentation tube's side walls. Generally the mechanism creating gravitational instabilities in apparatus of this kind during the settling process operates as follows: Portions of the suspension in the sedimentation tube are sheltered underneath measuring gear if present in the suspension (balance pan, plummet, etc.) or in small side-wall recesses formed by manometer connections. These sheltered portions are deprived, in the course of the sedimentation process, of their share of settling particles from the overlying portions of the suspension. Thus, their density, determined by particle content, decreases much faster than the density of the other parts of the suspension. Consequently, these portions become buoyant and, from time to time, pockets of fluid break away from those places, rising to the top, while being replaced by heavier suspension from underneath. This process repeats itself over and over, its disturbing effect being especially pronounced if the suspended material is only lightly graded. The method presented, on the other hand, does not require the presence of any measuring devices or ducts in the sedimentation tube. The excess density of the liquid employed outside the sedimentation tube serves to obviate any exchange of this liquid with the liquid inside. Thus complete gravitational stability of the settling column is ensured.

Sherman's advice to use, for the dispersion of soils, sodium hexa-metaphosphate instead of sodium hydroxide is gratefully accepted. Care should be taken, however, when going over to lower concentrations of solutes in the suspension, to increase the density of the clear liquid outside the sedimentation tube sufficiently to match the bulk density of the suspension. This may be accomplished by dissolving an inert chemical (additional amounts of dispersing agent, or sugar, glycerine, etc.) in the clear liquid.

Lin has succinctly pointed out that all methods of particle-size analysis based on sedimentation are prone to errors up to 20 pct, caused by mutual interaction between the settling particles in the suspension. Since interaction of this kind can be prevented by having the settling particles widely spaced in the suspension, this source of error is inherent only in such methods that necessitate the maintenance of a relatively high particle concentration during the measurements. The manometric methods mentioned by Lin, for instance, are essentially concentration-measuring methods and as such their accuracy is proportional to the concentrations employed; moreover, a definite minimum concentration exists below which measurements are impossible. (In the author's experience with manometric methods this minimum concentration was determined by the tendency of the fluid interfaces to stick to the manometer walls, which could not be overcome even by scrupulous cleanliness and frequent re-distillation of the manometer fluid.) The method described in the author's article, however, is in no way related to the concentrations of the particles in the suspension. Here the total submerged weight of the whole suspended sample is recorded, irrespective of the spacing of the particles. A suspension can be diluted to any degree suiting the purpose of the analysis, accommodated in a sedimentation tube of suitably increased width (or in a system of multiple sedimentation tubes), and the analysis carried out in the way described with the same accuracy of weight recordings as if the sample had been suspended in a small volume of fluid and placed into a narrow sedimentation tube. The author's method sets no lower or upper limit to the range of particle concentrations that have to be employed, except convenience. By this criterion the method is to be regarded as truly rigorous.

Alternatively, Lin suggested that the creation of a good suspension of a required type might be a baffling problem in the construction of a good instrument. Actually, no special type of suspension is required and a good instrument neither should nor does distinguish between good and bad suspensions; it reports the factual particle-size distribution in the suspended material at the time of the measurement. Particle sizes are recorded in terms of settling velocities, counting as separate particles all bodies or groups of bodies that have the faculty of moving independently in the fluid. If the discusser meant by good suspension one in which the degree of dispersion corresponds to a specific problem of practical application, this, depending on the specific practical problem, may be very hard to achieve or very easy to achieve. Yet it has no relevance to the method of particle-size determination itself.

The only requirement of a particle suspension, from the point of view of analysis, is that it be both homogeneous and non-turbulent at the beginning of the experiment. Lin rightly implies that it is often impossible to ensure both these requirements simultaneously if customary apparatus with fixed sedimentation tubes is used. Yet in the apparatus described both homogeneity and non-turbulence are automatically ensured at zero time of a run. This can be seen from the following details of procedure, requested by Lin. For the introduction of the suspension, which is to be analyzed, the sedimentation tube is taken out of the bath, inverted, and the suspension poured into it, stirring it up well and filling the tube up to the rim. Instantly the mouth of the tube is covered with a flat plate and the sedimentation tube turned end over end a number of times in quick succession. Thus time is allowed for the initial turbulence in the suspension to decay while homogeneity is preserved by preventing the particles in the suspension from starting to settle. In a tube of the given size not more than a minute is necessary, as a rule, for turbulence to decay. After this the tube is set upright (zero time of the experiment) and immersed in the bath in its proper position, the lid being pressed against its mouth all the time. To prevent the operator from wetting his hands, the lid is conveniently fitted with a long stem on one side, like a hoe handle. When the sedimentation tube has been placed into its final position, the lid is cautiously slid out sidewise. Instead of the plate, the honeycomb receptacle may be used for this purpose, if sturdily built and made to fit.

Lin is not correct when saying that an initially suitable rate of bead feeding may become too high during the later stages of the run, when sedimentation proceeds at a slower rate than at the beginning. While there would be no difficulty and no harm in switching to different feeding rates or to beads of smaller weight, this is not necessary. At the later stage merely more beads roll past unimpeded by the needle tip and line up in the recorder. Shortening the sedimentation column, shifting manometers to different heights during the run or other manipulations liable to affect the settling particles, are not needed since the apparatus can be left to work unattended during nights and holidays, whereas in the methods mentioned by Lin the runs have to be hastened by such manipulations to prevent the operators from having to work continuous shifts.

The method described is fundamentally free from the limitations and potential errors enumerated in the original article and the discussion. Conventional methods, on the other hand, do not claim rigor in these respects. Therefore, the method described is not comparable to conventional methods and must be checked experimentally against absolute methods. It has been proved to give correct results for artificially composed known material of the silt range (uniform fractions). It is now being checked for naturally graded material against optical size-analysis methods (microscopic measurement).

DISCUSSION OF

"INFLUENCE OF CAPILLARY CONDUCTIVITY AND DEPTH OF WETTING ON MOISTURE RETENTION IN SOIL"

by L. A. RICHARDS and D. C. MOORE

[Trans., v. 33, pp. 531-540, 1952]

T. J. Marshall (Division of Soils, Commonwealth Scientific and Industrial Research Organization, Waite Institute, Adelaide, South Australia)--The method developed by RICHARDS [1931] for measuring the permeability of unsaturated porous materials opened up quantitative studies in that field. Richards and Moore have introduced a welcome improvement by changing from vacuum to pressure control in their new apparatus.

The authors have collected in their Figure 1 the limited amount of published data available on capillary conductivity. Some additional data [MARSHALL, 1938] which were not available to the authors are given below in Table 3 for the sake of completeness.

Table 3--Capillary conductivity of two electrodialyzed soil colloids ($<2\mu$)

Source of material	Bulk density at time of packing	Soil-moisture tension	Capillary conductivity
	gm/cm^3	cm of water	cm/hr
Stockton clay	0.80	17	0.074
	0.80	43	0.034
	0.80	73	0.024
	0.80	95	0.013
	0.80	115	0.0019
	0.80	296	0.0002
Aiken clay loam	0.92	30	0.009
	0.94	54	0.011
	0.94	76	0.0074
	0.92	132	0.0018
	0.92	290	0.0002

Richards and Moore present evidence of movement of water at higher tensions than have been covered in earlier experiments. The method they used was to drop a small quantity of water onto loose dry soil and then follow the change with time in the water content of the wetted soil. This method does not provide a quantitative measure of capillary conductivity but gives an indication of whether water does or does not move. The question arises as to whether the observed movements were in fact due to flow of water as a liquid. It seems certain that vapor movement must have played some part more especially in those cases where the volume of soil wetted by adding only 0.1 ml of water would have been small.

To examine this point, the writer measured the movement of water from wet to dry soil under conditions which resembled those of Richards and Moore but which excluded any contribution from liquid flow. A container made of a double thickness of fine wire screen (90 mesh IMM) held 2.6 gm of soil in the shape of a cylinder about one cm in diameter. The soil was initially air dry and contained 11.1 pct of water. It had a 15-atmosphere percentage of 36. A little more than 0.1 ml of water was added to this soil and so raised its mean content to 15.8 pct. The cylinder containing the moistened soil was then placed in a small can and 30 gm of the same air-dry soil was poured in around the outside of the screen. The can was closed for one hour and then the amount of water lost from the cylinder and gained by the surrounding soil was determined.

It was found from this and another similar trial that one-third of the added water was transferred to the dry soil surrounding the cylinder. With vapor movement occurring to this extent, it is uncertain from the data presented by Richards and Moore whether liquid flow did occur at all at some of the higher tensions covered in their experiments.

While their experiments may not give critical evidence of liquid flow at high tensions, the writer is nevertheless in agreement with their contention that significant liquid flow probably does occur in such cases. The work of Richards on pressure membrane apparatus is in any case strongly indicative of this. In this laboratory the translocation of dissolved material has been used to distinguish between liquid and vapor movement in relatively dry soil. Movement of liquid has been observed at water contents well below the permanent wilting percentage in all soils examined and the order of magnitude of the conductivity has been determined. This technique has also been applied by GURR, MARSHALL, and HUTTON [1952] to the study of water movement due to a temperature gradient.

References

GURR, C. G., T. J. MARSHALL, and J. T. HUTTON, Movement of water in soil due to a temperature gradient, Soil Sci., v. 74, pp. 335-345, 1952.

MARSHALL, T. J., The water-conductivity functions of a kaolinitic and montmorillonitic soil colloid, Thesis, Univ. of California, 1938.

RICHARDS, L. A., Capillary conduction of liquids through porous mediums, Physics, v. 1, pp. 318-333, 1931.

L. A. Richards (U. S. Salinity Laboratory, Riverside, Calif., Authors' closure)--The remarks and data presented by Marshall are pertinent and well founded. Vapor transfer of water through soil is not negligible if the aqueous vapor-pressure gradient is appreciable. However, it has been my view that in the plant growth moisture range and in the absence of a temperature gradient, transfer by vapor is slow compared to transfer by film flow. LEWIS [1937, Fig. 7] used apparatus similar in principle to that mentioned by Marshall and found during steady-state moisture movement through a soil column that there was a large moisture discontinuity produced by a screen barrier permeable to vapor but not to film flow.

Reference

LEWIS, M. R., U. S. Dept. of Agr. Tech. Bull. 579, 1937.

DISCUSSION OF

"FROST PENETRATION INTO SOILS AS INFLUENCED BY DEPTH OF SNOW, VEGETATIVE COVER, AND AIR TEMPERATURES"

by CLYDE E. BAY, GEORGE W. WUNNECKE, and ORVILLE E. HAYS

[Trans., v. 33, pp. 541-546, 1952]

Nedavia Bethlahmy (Northeastern Forest Experiment Station, Upper Darby, Pa.)--One of the conclusions the authors draw is "that gypsum blocks can be used to measure the movement of frost into and out of the soil."

This is a valid conclusion. Gypsum blocks as well as the fiber-type blocks (nylon and fiberglas) indicate the presence of ground freezing by the high resistance offered to the passage of an electric current. However, the hydrologist is interested not in the mere presence of ground frost in general, but in the presence of a particular type of ground freezing. Some types are permeable to water, others are not. The two extreme types of frost are concrete and granular [POST and DREIBELBIS, 1942]. Concrete frost is impermeable, and does not permit infiltration. On the other hand, granular frost is permeable, and infiltration takes place readily.

The question that requires an answer is whether soil blocks can indicate the presence of the permeable or impermeable type of frost. Table 3 presents a few data on the resistances encountered in frozen soil of loam texture by fiberglas units.

Table 3--Soil-moisture resistance as related to frost type and moisture content

Sample	Moisture content	Frost type	Soil condition	Time in freezer	Resistance corrected to 60°F
	pct of dry wt			hr	ohm
1	1.7	No frost	Loose	24	3,000,000
2	13.4	Trace granular	Loose	24	3,000,000
3	20.8	Granular and concrete	Hard	24	270,000
4	32.2	Concrete	Hard	24	108,000
5	31.5	Concrete	Hard	18	3,300,000

All the samples in Table 3 show very high resistances, but not all of the samples are equally permeable to water. Sample 1 indicates a very high resistance. This sample was air dry at the start, with only 1.7 pct moisture; after being frozen for 24 hours, it was still as loose as at the beginning of the experiment. Samples 2 and 3 both had water contents below field capacity. But sample 2 had only 13.4 pct moisture, and when frozen had only a trace of granular frost, whereas sample 3, with only 7.4 pct more moisture, froze into a hard mass with both granular and concrete frost present. Samples 4 and 5 were both saturated. When frozen, both froze into a hard mass with concrete frost.

The values in Table 3 indicate that resistance alone does not convey the full frost picture. For each soil a detailed frost analysis must be made to interpret resistance figures in terms of type of frost.

There is one other factor that complicates the field analysis of frost conditions. Previous investigators [ANDERSON, 1946] have showed that when a soil is frozen, it draws moisture from the lower, unfrozen horizons. Consider then the following case:

A soil with a moisture content considerably below its field capacity freezes. It may freeze into the granular form of frost. Now, if the cold period continues for a long time, moisture will be drawn upwards from the unfrozen layer, and the horizon with granular frost will gradually be converted into concrete frost. At the same time, the resistance of the soil-moisture blocks may not indicate the change that is occurring. The high resistance that appeared when the soil first froze will continue to be high. But the observer will not know the significance of the high resistance in terms of the condition of the frost, that is, whether it is loose and permeable or hard and impermeable.

Table 4--Resistance of fiberglas blocks during successive days of freezing temperatures, Hazleton Stony Loam under Scrub Oak

Soil depth	1952				
	Jan. 28	Jan. 29	Jan. 30	Jan. 31	Feb. 1
inch					
Humus	4820	49000	65000	67500	11800
1.0	3525	4020	9000	58000	56500
2.0	9020	9600	10200	11000	11400
8.0	3090	3480	3925	4300	4950
13.0	2175	2575	2990	3300	3525
18.0	1800	2210	2550	2810	2975
Air T (°F)	33.4	15.1	1.1	8.8	24.7
T-32 (°F)	1.4	-16.9	-30.9	-23.2	-7.3
Cumulative T below 32 (°F)	0	-16.9	-47.8	-71.0	-78.3

Table 4 is presented to illustrate further the authors' conclusion regarding the effect of increasing temperature deficiency accumulations on the depth of frost penetration. Several interesting features should be pointed out in this table. On January 28 the average daily temperature was above 32°F and the soil was not frozen. During the next three days the temperatures were below freezing and the resistances of all units increased. However, the surface humus horizon froze on January 29, the next soil horizon froze only two days later on January 31, while the deeper soil horizons did not freeze at all during the period of observation. On February 1 the average daily temperature was below freezing, but two hours before the resistances were taken the air temperature rose to 38°F. This sudden increase in temperature was sufficient to thaw the humus and cause a slight drop in the resistance of the next horizon, but that was its maximum effect. The remaining units at the lower depths continued to increase in resistance.

References

ANDERSON, H. W., Effect of freezing on soil moisture and on evaporation from a bare soil, Trans. Amer. Geophys. Union, v. 27, pp. 863-870, 1946.

POST, F. A., and F. R. DREIBELBIS, Some influences of frost penetration and microclimate on the water relationships of woodland, pasture, and cultivated soils, Soil Sci. Soc. Amer., v. 7, pp. 95-104, 1942.

Clyde E. Bay (Soil Conservation Service, La Crosse, Wisc., Authors' closure)--It was satisfying to read that Bethlahmy also concluded the valid use of gypsum blocks to measure the movement of frost into and out of the soil. We are very much aware of the importance of the type of frost present in the profile during the winter and spring thaw periods. We also realize that the gypsum blocks may not indicate the type of frost present. In our measurements of frost penetration in the late '30's, using the King soil tube and hammer, we were able to sense the hardness of the frost in the process of driving the tube into the soil. The terms hard and soft were used to describe the type of frost present. The term soft, as we used it, applied to frost under various moisture conditions and was not limited to low moisture contents to which Bethlahmy applied the term granular.

Post and Dreibelbis used the descriptive terms concrete, honeycomb, and stalactite to designate the type of frozen structure. Most of the findings in our early work were similar to those of Post and Dreibelbis.

It was not the intent of this paper to report the type and permeability of frost present, but to present the practical application of gypsum blocks as a means of measuring the movement of frost into and out of the soil under Wisconsin weather conditions.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

MASON, BRIAN, Principles of Geochemistry, John Wiley and Sons, vii + 276 pp., 42 fig., 39 tables, 1952, $5.00.

Principles of Geochemistry developed from a course of lectures given by the author originally at Canterbury University College, New Zealand, and later at Indiana University. It is, therefore, in viewpoint, manner of presentation, and length, a textbook of geochemistry rather than a compendium of geochemical data. There has been a great need for such a book, not only in the classroom, but also for the use of already trained Earth scientists in becoming familiar with or bringing up to date their knowledge of the principles of geochemistry.

It is gratifying to find that the book has already been widely accepted and used in both ways. On a recent trip the reviewer found copies of the book, not only in university classrooms, but also on the shelves and in the brief cases of field geologists; it is mentioned frequently and consistently in informal discussions on geochemistry and in formal papers bearing on geochemistry and discussions thereof at scientific meetings.

The book begins with a brief introductory chapter defining geochemistry and giving a short history of the subject. There follow three chapters on The Earth in Relation to the Universe, The Structure and Composition of the Earth, and Some Thermodynamics and Crystal Chemistry. Magmatism and Igneous Rocks, and Sedimentation and Sedimentary Rocks are treated in one chapter each. It appears a little illogical to break in at this point with three chapters on The Hydrosphere, The Atmosphere, and The Biosphere before the third great group of rocks is dealt with in a chapter entitled Metamorphism and Metamorphic Rocks. However, the chapters after number four are more or less independent and can be read, or assigned in a course, in almost any order desired. The book closes with a short chapter on The Geochemical Cycle, in which the concept of the cycle is outlined, but no elements are followed through it as examples.

Principles of Geochemistry is clearly written and logically arranged. It contains sufficient material for a well-rounded course, and there are carefully chosen Selected References at the end of each chapter for those who desire to pursue particular subjects further.

It is necessary to be very concise to cover the subject of geochemistry in some 250 pages, but in some places the treatment is a little too concise. For example, in the table on page 140 the precipitation pH is given for various ions, but the original concentration of the ions is not stated. Variation in the original concentration can shift the precipitation pH as much as two or three units. Assuming that the values given apply to any original concentration can, therefore, lead to erroneous calculations and conclusions.

The book is nicely printed and adequately illustrated. It is remarkably free from typographical errors; the only one worthy of mention noted by the reviewer is in line 2 from the bottom of page 87 where temperature should read pressure. In a book covering so broad a field that is developing so rapidly there are bound to be some omissions, errors of fact or interpretation, presentation of controversial subjects where another point of view might also have been given, etc. Perhaps it will be in order to mention some of the more important examples.

On page 54, paragraph 2, lines 10-11, K^{40} is mentioned as a short-lived isotope. This is hardly in accord with current usage since K^{40} has a half life of ca. 1.5×10^9 years.

Paragraph 3, page 66, leaves the impression that it was Goldschmidt who started the x-ray study of crystal structure in 1912. Bragg is not mentioned in the text here or elsewhere in the book, nor are his classic early papers on the subject listed among the selected references.

Paragraph 4, page 86, does not mention chalcedony although it is probably more abundant than any of the forms of silica mentioned there, except quartz.

Page 118, paragraph 2, line 2, "difference in ionic radius and ionic charge"; and should read or because a sufficiently great difference in either radius or charge will eliminate the possibility of substitution.

On line 7, page 123, B_2O_3 is listed as a volatile compound. Actually B_2O_3, when pure, is little, if any, more volatile than SiO_2. Only when it combines with H_2O to form H_3BO_3 does the boron become volatile.

At the bottom of page 170 Mason remarks that the amount of material in solution contributed to the sea annually by runoff from the land is "only an infinitesimal fraction" (5.5×10^{-8}) of the amount the sea now contains. It should be pointed out that, considering the length of geologic time, this amount per year is not at all insignificant. If the rate has been constant in the past, in 100 million years, which is a small part of geologic time, 5 1/2 times as much material would have gone into the oceans in solution as we find there now!

On page 176, lines 11-13, the statement is made that the primitive ocean was probably small in proportion to the existing hydrosphere. This idea is gaining credence from repetition although there is no direct evidence for it. Indeed, there is much evidence to the contrary. That the continents and ocean basins have had their present (at least vertical) relationships since early geological time is widely acknowledged. Yet there are marine Precambrian sedimentary rocks well up on the continental platforms, so the ocean basins must have been filled to overflowing during lower to middle Precambrian deposition.

On page 179, it is stated that gravitational separation of gases in the atmosphere does not become significant "until above 150 km." No determinations have yet been made at such heights, but separation has been demonstrated for samples collected at 65-70 km. In paragraph 3, page 181, H_2 and He are said to be capable of escaping from the Earth's gravitational field. It should be pointed out that this belief is the result of calculations based on assumptions that have not been proven. No actual current escape of gases from the Earth has been demonstrated, although there is excellent evidence that such escape has occurred in the past.

On page 251, in discussing the sources of energy in the geochemical cycle, Mason says "Solar energy operates only in the atmosphere and at the surface of the Earth." If the idea is correct that deposition of sediments in geosynclines produces elevation and folding of adjacent areas, then solar energy may be indirectly responsible for almost all continental tectonics since the primary differentiation of the Earth's surface into continental masses and ocean basins. These effects extend to depths of some miles, so in this case solar energy could be considered to operate some distance from the surface.

This treatise is well rounded, fundamentally sound, and conservative. The author has used good judgment in selecting and presenting material. For example, the treatment of thermodynamics and crystal chemistry is admirably tailored to fit a work of this scope and for the intended audience, but there is an anomaly in that Mason devotes space to deriving thermodynamics that he then never uses. The discussion of diffusion in geological processes [pp. 215-216] is brief and to the point; the subject is disposed of neatly in the light of laboratory and field evidence. There is no need to predict that the book will be useful and make a high place for itself in the literature of the Earth sciences; it has already done so on its merits, without the benefit of reviews or abnormal advertising.

EARL INGERSON

BRITISH ATOMIC ENERGY RESEARCH ESTABLISHMENT, Harwell, the British Atomic Energy Research Establishment, 1946-1951, Philosophical Lib., New York, and H. M. Stationery Office, London, 128 pp., 32 pl., 9 fig., 1952, $3.25.

This brief, clear, and interesting volume is written to acquaint the intelligent layman or the scientist in fields not closely connected with nuclear studies, with the experimental program at the British equivalent of the U. S. National Laboratories or of the Canadian Chalk River Laboratories. In nine short chapters are contained an account of the setting up of the Establishment, the programs under way - production of controlled nuclear energy, production of isotopes, studies on reactor mechanisms, studies on production of accelerated particles (via cyclotron, Van de Graaf generator, and the like), health studies and radiation protection, and other research.

Appendices list the senior staff members, outline the mechanisms of the two reactors Gleep and Bepo, give a bibliography of the scientific papers by the staff of Harwell, and give a well-chosen reading list and a glossary of the technical terms used in the text. Being an official British Government report, no authors' names are given.

The active nuclear physicist will find little new matter. The scientist interested in learning what is going on outside his own field will find this little book extremely interesting. Would that the U. S. Atomic Energy Commission get out a similar authoritative account of its own unclassified work!

JOHN PUTNAM MARBLE

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NOTES AND PERSONALIA

NOTES

Corrigendum--In the issue of June, 1953, in the paper by William L. Donn, page 471, in the fourth line above the figures, the reference should be to Figures 3 and 5 (not 3 and 4), and in the second line above the figure the reference should be to Figures 4 and 6 (not 5 and 6).

Awards for 1954-55 under the Fulbright Act--Applications for Fulbright awards for the academic year must be sent to the Conference Board of Associated Research Councils, 2101 Constitution Avenue, Washington 25, D. C., by October 15, 1953. These awards are made for university lecturing and for advanced research in various fields in Austria, Belgium, Denmark, Egypt, Finland, France, Germany, Greece, Iraq, Italy, Japan, Luxembourg, Netherlands, Norway, Pakistan, Sweden, and the United Kingdom and colonial dependencies. The awards for study are at the post-doctoral level. Interested persons should write to the Board at the address given.

Meeting of the URSI Committee--The Fall Meeting of the USA National Committee of the International Scientific Radio Union will meet jointly with the Canadian National Committee and the Professional Group on Antennas and Propagation of the Institute of Radio Engineers in Ottawa, Canada, October 5-8, 1953. The following Commissions will take part: (1) Radio Measurement Methods and Standards; (3) Ionospheric Radio Propagation; (4) Terrestrial Radio Noise; (5) Radio Astronomy; and (7) Electronics. Interested persons should get into touch with the Secretary of the USA National Committee, URSI, W. E. Gordon, School of Electrical Engineering, Cornell University, Ithaca, N. Y.

New Japanese publication on atmospherics--Volume 1 of the *Proceedings* of the Research Institute of Atmospherics of Nagoya University, Toyokawa City, Aichi Prefecture, Japan, has arrived in the United States. Eleven papers and three notes appear in this first volume, which contains 106 pages. These are listed in the Bibliography in Terrestrial Magnetism in this issue of the *Transactions*.

New Indian publication on Geophysics--Volume I, No. 1, of the *Geophysical Digest*, issued quarterly by the Secretary of the Central Board of Geophysics, 27, Chowringhee, Calcutta, 13, India, has arrived in the United States. This first volume of 55 pages contains news items and bibliography, some annotated, in the various fields of Geophysics. The *Digest* will publish a bibliography of Indian publications and items from other sources relating to India.

New oceanographic periodical--Publication of *Der Seewart*, nautical journal for the German merchant marine, established in 1932 and suspended in January, 1945, has been resumed by the

German Hydrographic Institute in Hamburg. The quarterly journal emphasizes the application of geophysics to the problems of the mariner, especially in the fields of meteorology, oceanography, and terrestrial magnetism.

New oceanographic vessel--The steel, auxiliary three-masted schooner yacht Atlantic, recently acquired by the Texas A. and M. Research Foundation, has been commissioned honorary flagship of the Texas Navy. The 120-ft vessel is being converted and equipped to conduct oceanographic surveys in the Gulf of Mexico and neighboring waters.

Studies of the volcanic range Iztaccihuatl in Mexico--Investigations of this range are under way as a part of a continuing program of study of the higher Mexican volcanoes. Work was begun in 1953 under the direction of Sidney E. White of Ohio State University. Glacial deposits and moraines in three valleys in the southwest side of the range varying roughly from 10,000 to 16,000 ft were mapped on aerial photographs. There is evidence of four glacial substages, probably all of Wisconsin age, with smaller moraines in front of three glaciers indicating minor pulsations, probably within the last 3000 years.

Coral Atoll Project continues--The Coral Atoll Project sponsored by the Pacific Science Board of the National Research Council will conduct studies through its fourth year on Ifaluk in the Western Carolines, going into biological and physical aspects of the island. Among the AGU members engaged in the study are Joshua I. Tracey, Jr., and Theodore Arnow.

Course on the geodetic measurement of distances--The Geodetic Institute of the Technische Hochschule in Munich, in cooperation with the Institut für Angewandte Geodäsie at Frankfurt am Main and the Deutsches Geodätisches Forschungsinstitut, is offering a course for the geodetic measurement of distances from September 14-30, 1953. Various of the latest types of instruments will be demonstrated. Interested persons should write to the Technische Hochschule.

Research program of the Arctic Institute of North America--Thirty-one research projects, sponsored by the Arctic Institute of North America, and supported by the Office of Naval Research, are under way in the Arctic and Subarctic areas of North America bearing on many aspects of geophysical sciences as well as on linguistics, economics, and diverse fields.

PERSONALIA

Roger Adams, Head of the Department of Chemistry at the University of Illinois, Foreign Secretary of the National Academy of Sciences, and Chairman of the Policy Committee of the Office of International Relations of the National Research Council, has been designated as the recipient of the August von Hoffman Award of the German Chemical Society.

Jackson M. Barton, formerly with the Deep Rock Oil Corporation in Tulsa, Oklahoma, has taken the position of Exploration Manager of the Northern Natural Gas Producing Company in Omaha, Nebraska.

K. Hilding Beij, Acting Chief of the Hydraulics Section of the National Bureau of Standards and recently retired General Secretary of the AGU, has retired from his position at the National Bureau of Standards where he served for 32 years.

Hugo Benioff, Professor of Seismology at California Institute of Technology, and Vice President, Section of Seismology, AGU, has been appointed on an advisory panel of the National Science Foundation, representing geophysics.

Francis Birch, Professor of Geology at Harvard University, and President of the Section of Tectonophysics, AGU, has been elected Vice President for Mathematical and Physical Sciences in the American Academy of Arts and Sciences. He has also been appointed Chairman of the Division of Earth Sciences of the National Research Council.

Lyman J. Briggs, Director of the National Bureau of Standards, retired, has been given an award of the Scientific Apparatus Makers Association for achievement in relation to his work in the scientific and technical professions.

Detlev W. Bronk, President of the National Academy of Sciences and of Johns Hopkins University, has resigned from the latter position to become Head of the Rockefeller Institute for Medical Research.

Carey Croneis has resigned as President of Beloit College to become Provost of Rice Institute, where he will also serve as Head of the Department of Geology.

Harold N. Fisk, Chief of the Geological Research Section of the Humble Oil Co., has been awarded the James Laurie Prize of the American Society of Civil Engineers for his paper "Mississippi River Valley Geology Relation to River Regime."

Paul D. Foote, Executive Vice President of the Gulf Research and Development Co., has been awarded an honorary doctorate by the Carnegie Institute of Technology.

H. Richard Gault is on leave from his duties as Professor of Geology at Lehigh University and is serving as Executive Secretary of the Division of Earth Sciences at the National Research Council.

Frank J. Haight, Oceanographer and Chief, Section of Currents in the Division of Tides and Currents, U. S. Coast and Geodetic Survey, retired June 30, 1953, after more than 32 years of service.

Charles B. Hunt, Chief of the General Geology Section of the U. S. Geological Survey with headquarters in Denver, has been appointed Executive Director of the American Geological Institute, effective September 1, 1953. He will succeed Robert W. Webb who has undertaken this work since January 1, 1953, while on leave from his post as Professor of Geology at the Santa Barbara Campus of the University of California. Upon his return to Santa Barbara in September, he will also serve as Chairman of the Department of Physical Sciences.

Arthur T. Ippen, Professor of Hydrodynamics at Massachusetts Institute of Technology, has been awarded the Karl Emil Hilgard Prize of the American Society of Civil Engineers for his paper "Mechanics of Supercritical Flow."

Orson W. Israelson of Utah Agricultural Experiment Station has been awarded the John Deere Gold Medal of the American Society of Agricultural Engineers.

Howard A. Meyerhoff has relinquished duties as the Administrative Secretary of the American Association for the Advancement of Science and has taken up duties as the President of the recently organized Scientific Manpower Commission.

LeRoy Scharon, Associate Professor of Geology at Washington University, St. Louis, has been named a member of the Executive Committee of the Division of Mining, Geology, and Geophysics of the American Institute of Mining and Metallurgical Engineers.

H. W. Straley, III, is engaged during the current field season in geophysical investigations of chromite deposits in North Carolina.

Francis M. Van Tuyl, Head of the Department of Geology at Colorado School of Mines, has retired from that position. He has been at the Colorado School of Mines since 1917, and has been Head of the Department since 1919.

Carl P. Vetter, Chief of the Regional Office of River Control of the Bureau of Reclamation, is on leave, devoting his services to the solution of river control and diversion problems of the Government of Iraq. While on this work, he is associated with the consulting firm, Knappen-Tippetts-Abbett-McCarthy, which is engaged in the planning of various water-control structures in Iraq.

Daniel E. Whelan, Jr., who has been on duty as an officer of the U. S. Coast and Geodetic Survey for the past ten years, is returning to Loyola University of Los Angeles as Dean of the College of Engineering.

Harold G. Wilm, Chief of the Division of Forest Influences, U. S. Forest Service, and recently elected President of the Section of Hydrology, AGU, will leave his post with the Forest Service and take up duties, as of September 1, as Associate Dean of Biological Sciences and Graduate Studies in the College of Forestry of Syracuse University.

Elmer H. Finch, geologist with the Geotechnical Corporation in Dallas, Texas, died April 29, 1953, at the age of 69. He was born at West Troy, Michigan, and attended George Washington University from 1905-1910. He was in the service of the U. S. Geological Survey from 1911 to 1920, worked for several oil companies in the succeeding period, and, in 1943, undertook duties with the Petroleum Administration for War. In 1947, he entered the services of the Geotechnical Corporation. He had been a member of AGU since 1947.

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MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of May 6, 1953

Thee meeting was called to order at 19h 30m in the Board Room of the National Research Council - National Academy of Sciences Building, 2101 Constitution Avenue, Washington, D. C., by President Walter H. Bucher. The newly elected officers, though they do not take office until July 1, 1953, were invited to attend.

Present--Thirty-eight persons were present, namely: L. H. Adams, L. R. Alldredge, W. W. Atwood, Jr., Robert Balk, K. Hilding Beij, Francis Birch, Walter H. Bucher, Wilbur S. Burbank, James J. Capello, Felix Chayes, Phil E. Church, Ernst Cloos, H. N. Eaton, R. H. Fleming, Harry H. Hess, M. King Hubbert, Woodrow C. Jacobs, J. Wallace Joyce, Walter D. Lambert, Walter B. Langbein, Esper S. Larsen, Jr., James B. Macelwane, John Putnam Marble, Walter H. Munk, Jerome Namias, James A. Peoples, Jr., Donald W. Pritchard, Mary C. Rabbitt, F. W. Reichelderfer, Elliott B. Roberts, W. W. Rubey, M. B. Smith, Waldo E. Smith, Harlan T. Stetson, Victor Vacquier, F. J. Veihmeyer, James T. Wilson, and Ralph N. Wilson. The following were excused: Roger J. Adams, Fred Anderegg, Hugo Benioff, J. A. B. Bjerknes, H. F. Blaney, Perry Byerly, H. R. Byers, F. L. Culley, Morgan D. Dubrow, E. A. Eckhardt, Maurice Ewing, Jno. A. Fleming, W. F. Foshag, R. C. Gibbs, Beno Gutenberg, H. W. Hemple, R. R. Heinrich, Benjamin Holzman, A. J Hoskinson, Earl Ingerson, C. E. Jacob, H. R. Joesting, R. K. Linsley, G. A. Macdonald, M. A. Mason, G. F. McEwen, G. Medina, L. M. Murphy, Frank Neumann, A. C. Redfield, R. R. Revelle, Irwin Roman, M. O. Schmidt, L. B. Slichter, L. G. Straub, T. P. Thayer, W. T. Thom, Jr., J. Verhoogen, R. H. Weightman, H. C. Willett, H. G. Wilm, and George P. Woollard.

The Executive Secretary read the names of the new officers of the Union and of the Sections for the triennium beginning July 1, 1953, introducing those present.

Approval of Minutes--The minutes of the meeting of November 7, 1952, published in the December, 1952, issue of the Transactions, pages 933-942, were approved.

General Secretary's Report

General Activities

Executive Committee--J. Verhoogen of the University of California, Vice President of the International Association of Volcanology, recently became a citizen of the United States, which makes him a member of our Committee.

Representation in other organizations--David J. Varnes of the U. S. Geological Survey has recently been appointed AGU representative on the American Geological Institute's Committee on Glossary.

Financial report--The report of the Committee on Audit, page 939 in the December, 1952, Transactions, gives the audited financial statement for fiscal year 1952. Our cash balance as of May 1, 1953, is approximately $19,700 as compared with $19,275 a year ago, $18,500 two years ago, and $15,370 three years ago. As compared with a year ago, our Permanent and Emergency Funds have increased more than $2,700, bringing them to a total of $9,878.16.

Membership--Our membership as of May 1, 1953, is 5,000 as shown below.

Membership, November 5, 1952	4,807	
New members, November 5, 1952 - May 1, 1953	316	
Reactivated	9	5,132
Resignations	88	
Dropped	25	
Inactive	5	
Deceased	14	132
Membership, May 1, 1953		5,000

Those reported as deceased since our last meeting are as follows: E. W. K. Andrau (Sept. 20, 1951), Joseph A. Sharpe (May 9, 1952), Franklin P. Ulrich (July 3, 1952), Walter Riddell (Aug. 17, 1952), Monroe G. Cheney (Sept. 18, 1952), Frank H. Tyro (Oct. 20, 1952), Gilbert O. Harris (Dec. 4, 1952), F. R. Moulton (Dec. 7, 1952), William H. Hobbs (Jan. [illegible], 1953), Thos. A. Jaggar (Jan. 17, 1953), Fayette S. Warner (Jan. 23, 1953), John C. Kennedy (Feb. 14, 1953), David Thaler (Apr. 1, 1953), and George R. Wait (Apr. 9, 1953).

One hundred and eighty-one members have not yet paid dues for 1951 to 1953 and in accordance with the instructions of By-Law 13 it is recommended that they be dropped from the rolls of the Union after one further attempt to bring them into good standing. In addition, 180 have not yet paid dues for 1952 and 1953. We have over 40 applications for membership in hand.

Meetings and regionalization--The Twenty-Ninth Regional Meeting was held at Stanford University, February 6-7, 1953, with the Sections of Meteorology and Hydrology joining. About 250 were in attendance at the Regional Meeting, which was reported as being very good.

A new Regional Committee has been elected for the Pacific Southwest Regional Area which will take office on July 1. It is the plan, we believe, that there will be a meeting somewhere in California again in February, 1954, but details are awaiting the action of the new Committee.

The Thirty-Fourth Annual Meeting had a registered attendance of 804, with perhaps a total attendance well exceeding 1000. The Section of Meteorology joined with the American Meteorological Society in one session.

The Thirtieth Regional Meeting is planned for Minneapolis on August 31, 1953, on the day preceding meetings of the International Association for Hydraulic Research and the Hydraulics Division of the American Society of Civil Engineers. Martin E. Nelson is the Chairman of the Regional Committee.

The American Association for the Advancement of Science is urging us to co-sponsor meetings on geophysics at their annual meeting to be held in Boston just after Christmas, 1953. We have heard nothing more about the suggested meeting in memory of William Bowie that was discussed at our last Executive Committee meeting.

Since presentation of papers at meetings is not required for publication, it is suggested that presentation of papers by title on the program of a meeting is no longer necessary and might be eliminated.

Publications--We are now publishing the Transactions in an edition of 5600, which, with the late rapid increase in membership since the beginning of the year, perhaps is not even enough. About 5200 copies of the April issue were mailed on April 27 to members and subscribers. Over 1000 of these go to foreign addresses and about 20 to student subscribers.

Recently our Honorary President, John A. Fleming, transmitted for publication an extensive history of the American Geophysical Union, outlining its scientific and other activities from the beginning in 1919 to June 30, 1952. This will be published in a subsequent issue of the Transactions.

The microcarding project of the Society of Exploration Geophysicists is now proceeding on a trial basis through 1953 and 1954. No report has been received thus far.

A paper by Frank H. H. Roberts on "Carbon 14 dates and archeology" published in our Transactions has been selected for reprinting in the Smithsonian "Panorama of Science."

Elections--A Committee of Tellers, totaling 25, was appointed to tally the results of the recent election in which about 2000 ballots were cast. Earl Ingerson was designated Chairman. Although the present officers remain in office until June 30, 1953, it is felt that these next few weeks should be looked upon as a period of turning over the reins and indoctrinating the new officers so that by July 1, 1953, when they take office, they will be fully ready to proceed with their duties, perhaps even having made the Committee appointments for their administrations.

Administration of the Union--The Carnegie Institution of Washington has graciously granted the Union quarters through next January, though it may be necessary for us to relinquish a small amount of the space that we now occupy.

In accordance with the action taken at the November 7, 1952, meeting of the Executive Committee, President Bucher appointed a Committee on the Relations of the American Geophysical Union with the National Research Council consisting of F.W. Reichelderfer (Chairman), L.H. Adams, K. Hilding Beij, and John A. Fleming, the President serving ex-officio, and a Committee on Nomination Procedures which consists of L. H. Adams (Chairman), Ernst Cloos, and H. W. Hemple.

Honorary President Fleming has continued his efforts toward the raising of funds for a medal in Terrestrial Magnetism and Electricity.

News items--President Bucher appointed Roger Revelle to act as his representative at the inauguration of the new President of San Diego State College.

The National Science Foundation has begun the issuance of a List of International and Foreign Scientific and Technical Meetings, the last one being dated April 1, 1953. This, to a certain extent, duplicates one put out in England for the coming International Scientific and Technical Conferences, which lists many meetings that the National Science Foundation does not list, including the meetings of the AGU.

Activities as Committee on Geophysics of the National Research Council

Grant for 1954--Tentative word indicates that our usual grant of $400 for the coming fiscal year will be made by the National Research Council.

International Geophysical Year--The American Committee on the Geophysical Year (Third International Polar Year) has been appointed, with Joseph Kaplan of the University of California as Chairman.

Instrumentation oceanographic research--At the request of the International Association of Oceanography, we requested various groups doing work in oceanography in this country to send information concerning field instruments for oceanographic research to the International Association.

Tenth General Assembly of IUGG--Recent word from General Secretary Laclavère has indicated that the Tenth General Assembly will be held in Rome, September 15-29, 1954. He advises further that a list of the main topics submitted for discussion during the meetings of the Associations will be sent to the various National Committees within a month. More detailed information on the program of work of the Union and of its Associations, Joint Commissions, etc., will be published in the IUGG News Letter. The program for Geodesy was published in April, 1953, and should arrive in this country soon. The Executive Committee of the IUGG has decided not to limit the number of delegates from each country nor the number of members of families accompanying them. However, a resolution was adopted to recommend to National Committees to be careful to avoid having the Assemblies grow too unwieldy. Laclavère also advises that there are to be three categories of participants: (1) the official delegates, (2) other men of science attending the meeting, and (3) members of families of those in (1) and (2). It was resolved that those in the second and third groups should pay a reasonable registration fee, say about $9.00.

It is important that we start thinking seriously about matters relating to this Assembly, both with regard to program and delegations. In 1951 the President of the Union was rightly designated as the Chief Delegate from the United States and the other officers of the Union, insofar as they were available, were designated as official delegates. In addition, a representative to each of the seven Associations was designated, this in most instances being one of the officers of the related Section. The matter of the American delegation should be settled insofar as is possible by late fall or early winter, and the new administration should take early steps in the matter of making recommendations through the Office of International Relations of the NRC to the State Department.

The IUGG now has a News Letter which is being sent to members of the present Executive Committee plus certain others. There are about 200 on the list of recipients in the United States.

No recent word has come concerning the roster of geophysicists that General Secretary Laclavère is compiling.

The IUGG has requested the establishment of two depository libraries in the United States to receive all publications of the International Union and its Associations. The New York Public Library and the Library of the University of California at Los Angeles have indicated willingness to assume the responsibility of serving as these depositories.

Other international meetings--We have received a communication from our former President, W. C. Lowdermilk, who is now in Israel, pointing out that the Exhibition on the Conquest of the Desert is to be held in Israel in the autumn.

The Fourth Congress of the International Association on Quaternary Research is to be held in Italy, August 30 to September 10, 1953. This is probably of interest to many of our members.

The Third International Conference on Soil Mechanics and Foundation Engineering will be held in Zurich, Switzerland, August 16-25, 1953.

Library of Congress list of international organizations--In response to an inquiry from the Library of Congress, we have supplied extensive information concerning the IUGG, the constituent Associations, Commissions, etc., to the Library.

K. Hilding Beij, General Secretary

Action on the General Secretary's Report--The report was accepted.

Action on Recommendations of the General Secretary--The recommendations of the General Secretary with respect to members who had not paid dues from 1951 to 1953 were approved.

A motion that we should discontinue the listing of papers by title in the program of the Annual Meeting was adopted.

The President suggested action should be taken as early as possible regarding delegates to the Tenth General Assembly of the IUGG in Rome in 1954.

International matters--Honorary President Fleming, who was unable to be present, transmitted the report shown in Appendix 1, which was read by the General Secretary.

Medal in Terrestrial Magnetism and Electricity--The General Secretary read the report from Honorary President Fleming shown in Appendix 2. After considerable discussion of the pros and cons of a medal versus other modes of recognition or award, it was voted that the incoming President should appoint a committee to examine, with Dr. Fleming, the desirability of making an award in this field and the nature of such an award.

Introduction of the new President--President Bucher introduced President Elect Macelwane who addressed the group briefly and informally, speaking of the record of his predecessors and inviting cooperation and assistance.

Plans for the International Geophysical (Third Polar) Year--Elliott B. Roberts was invited to the meeting to report on plans that are developing for the Geophysical Year 1957-1958 as shown in Appendix 3. This was discussed briefly.

Reports of Standing Committees

Meetings--Chairman Marble presented the report shown in Appendix 4, which was accepted. He called for specific or general topics for next year's annual meeting, and it was noted that W. C. Krumbein has suggested "Applications of statistical methods to geophysical data" as a subject for a symposium.

It was approved that the Executive Committee consider holding its meeting, if feasible, on the Sunday preceding the Annual Meeting, instead of the Wednesday evening following the Annual Meeting.

Budget--Chairman Eaton presented the report of the Committee. There was extensive discussion of the report, and, after one minor modification, it was adopted as shown in Appendix 5.

Audit--In the absence of Chairman Weightman, the Executive Secretary read the report presented as Appendix 6. The report was accepted.

Reports of Special Committees

Relations of the American Geophysical Union and the National Research Council--Chairman Reichelderfer of this Committee, which was authorized at the Executive Committee meeting of November 7, presented a draft of a report which he desired to get in final shape, following which he felt that the Committee should be discharged. The final report will be published subsequently. President Bucher outlined a few very recent developments relating to the conflicting opinions on how the functions of the NRC may best be served in geophysics. There was extensive discussion of the matter.

Cosmic-Terrestrial Relationships--Chairman Stetson briefly summarized the report shown in Appendix 7.

William Bowie Medal--Chairman Lambert made a brief oral report, advising that the record of the Committee's deliberations and techniques would be filed in the office of the Union for the guidance of future committees.

Resolutions--Chairman Rabbitt asked who should receive Resolution 6 on Science in Government, adopted at the Business Meeting during the afternoon. It was decided that this be sent to the daily press and to Science.

National Research Council

Office of International Relations--Director Atwood spoke hopefully of the problem of representation at international meetings, feeling that ways and means will be found to send desired delegations.

Affiliated Organizations

American Geological Institute--In the absence of George P. Woollard and E. A. Eckhardt, the Directors from AGU on the Board of the Institute, John P. Marble, representing another group on the Board, gave a brief report on most recent developments in the Institute.

American Standards Association Committee on Permeability Z59--In the absence of C. E. Jacob, M. King Hubbert, who is also a member of the Committee, gave a brief report on the activities and plans of the Committee.

American Association for the Advancement of Science--John P. Marble, AGU representative on the Council of the AAAS, stated he felt that perhaps the most tangible benefit of our affiliation is the opportunity to organize meetings in connection with AAAS where it might not be desirable or possible to organize a meeting solely our own.

Adjournment--The meeting adjourned at 22h 30m.

K. Hilding Beij, General Secretary
Waldo E. Smith, Executive Secretary

APPENDIX 1--REPORT ON INTERNATIONAL SCIENTIFIC RELATIONS

J. A. Fleming continued to act as American agent for dollar funds of the International Union of Geodesy and Geophysics at the request of the General Secretary. The receipts included

Dues	
USA, 1952	$ 2,240.00
Canada, 1953	1,118.37
Philippines, 1951	556.00
Grants from UNESCO	3,937.94
Cash balance on June 1, 1952	6,813.35
Total	$14,665.66

Disbursements (upon authorization of General Secretary) included

By checks Nos. 71 through 77	$ 5,457.48
Balance as of May 6, 1953	9,208.18
Checking total	$14,665.66

The Report of IUGG on the Ninth General Assembly at Brussels in 1951 was published in 1953. It lists the officers for 1951-1954 and all officers of the Associations [see Transactions, v. 32, p. 787, 1951]. The Finance Committee, with J. Tuzo Wilson of Toronto, Canada, as President, and four other members, was continued. Also listed are Joint Commissions with other Unions: (1) on Solar and Terrestrial Relationships (with IUA, URSI, UTAP, and with four members of IUGG from ATME and AM); (2) on Oceanography (with UBS and five members of IUGG from AO); (3) on the Ionosphere (with AU, URSI, UTAP, and four members of IUGG from ATME); (4) on Radio-Meteorology (with URSI and four representatives of IUGG from AM); and (5) on High-Altitude Research Stations (with UBS, AU, UPAP, and two representatives each of IUGG from AM and AH).

Under the new Statutes by which ICSU is incorporated under the laws of Belgium and which provide for an elected Treasurer, W. A. Noyes, Jr., of the United States was elected Treasurer in October, 1952, at the meeting held in Amsterdam of the Executive Board of ICSU. He took over the dollar account of ICSU, which was previously at the Riggs National Bank in Washington in charge of J. A. Fleming. The transfer was effective as of October 31, 1952 (the end of the ICSU fiscal year). The detailed transfer statement for the fiscal year ended October 31, 1952 (subsequently audited and found correct in all particulars), showed total receipts of $32,708.89 and total disbursements of $17,279.80 (by checks 69 through 94, upon authorization of the General Secretary of ICSU); the balance of $15,429.09, in accordance with the Riggs National Bank statement, was transferred to the new Treasurer and his receipt taken therefor.

Jno. A. Fleming

APPENDIX 2--MEMORANDA REGARDING THE PROPOSITION FOR A MEDAL AND HONORARIUM FOR SCIENTIFIC ATTAINMENT IN TERRESTRIAL MAGNETISM AND ATMOSPHERIC ELECTRICITY

The magnetic and electric fields of the Earth for the past half century have been and are presently of growing importance in many theoretical studies and applications. They have been particularly valuable in economic reconnaissance surveys for the determination of areas favorable to oil prospecting. This discipline of the American Geophysical Union would benefit were there established an honor in recognition of good work done, both as regards theoretical and practical application. This objective would be forwarded by the award every two or three years of a medal for outstanding research and achievement in this branch of Geophysics through the American Geophysical Union and the Executive Committee of the Union, which functions as a Committee on Geophysics of the National Academy of Sciences through the Academy's National Research Council. Chief among the desiderata are (1) the enlistment of a larger group of trained and qualified investigators, and (2) the encouragement of younger men of promise to take up specialized training.

It is hoped that means may be found to endow such a medal for distinguished attainment in advancing cooperative research in Terrestrial Magnetism and Atmospheric Electricity, and for travel expenses of recipients to and from Washington or of a suitable honorarium. It is estimated that an endowment sufficient for these purposes would be:

For designing and making of dies for the medal	$ 5,000
Fund to provide, through accumulated annual interest, travel expenses of, or honorarium to, recipients of the Medal	$ 5,000
Total	$10,000

This is to report that solicitations for funds sent some 20 prospective donors (since December, 1952) have with only one exception been very favorable to the suggestion. Already pledges of $1000 each have been received from C. F. Kettering Foundation of Detroit, Vulcan Copper and Supply Co. of Cincinnati, and Gulf Research and Development Co. of Pittsburgh. Besides these, a very limited circularization to members and friends of the Union has resulted in pledges totaling $400. Thus the tentative suggestion has now pledges totaling $3400, about one-third of the total required.

It is hoped that, with this initial effort, the Executive Committee of the Union may extend its approval of the idea and arrange for a suitable committee to execute the project.

Jno. A. Fleming

APPENDIX 3--REPORT ON THE ACTIVITIES OF U. S. NATIONAL COMMITTEE FOR THE THIRD GEOPHYSICAL YEAR

A U. S. National Committee has been formed and started work toward effecting a program of great interest to the Union. Geophysicists, aware of the concerted work achieved in the First Polar Year 1882-3, and its successor in 1932-3, now perceive the great value of a third international attack upon the problems of geophysics. We are approaching an epoch 25 years after the Second Polar Year and the time of another sunspot maximum. Some discussion of this has occurred in the latest assemblies of several of the international scientific unions.

In October, 1952, the International Council of Scientific Unions set up a Special Committee for the International Geophysical Year 1957-8. This consists of the following:

International Astronomical Union--N. E. Norlund (Denmark), M. Nicolet (Belgium), and an alternate to be appointed by the Union.
International Union of Geodesy and Geophysics--J. Coulomb (France), V. Laursen (Denmark), and one member to be appointed.
International Geographical Union--J. M. Wordie (Great Britain).
International Scientific Radio Union--L. V. Berkner (U. S. A.), W. J. G. Beynon (Great Britain), and M. Boella (Italy).
World Meteorological Organization--J. Van Mieghem (Belgium), and one member not yet appointed.
International Council of Scientific Unions--E. Herbays (Belgium).

A letter was addressed by E. Herbays, Provisional Secretary, to the above Unions requesting their views as to a detailed program of observations. The same communication pointed out two views adopted by ICSU: first, to extend the scope of observations to the entire world, thus making it an "International Geophysical Year" instead of a "Polar Year"; and second, to undertake a world longitude survey. It was also urged that the Unions consider which problems particularly demand international cooperation. The latter view suggests that interest has centered mainly about problems in the physics of the atmosphere, where broad-scale simultaneous observations and synoptic treatment are needed, and generally less upon the physics of the solid Earth. The Special Committee believes that modern geophysical knowledge has opened important new opportunities for achievement through such a program and suggests tentatively the following: (1) the dynamical study of the upper atmosphere through the observation of winds by ionospheric, geomagnetic, meteorological, and astronomical methods; (2) study of atmospheric tides by ionospheric methods, to which would be added geomagnetic and meteorological methods in the case of permanent or semi-permanent stations; (3) the morphology of perturbations in the upper atmosphere by combined observations on the ionosphere, terrestrial magnetism, and telluric currents, and by spectroscopic observations (aurora, twilight, and night sky), coupled with precise observations of solar phenomena.

The General Secretary of ICSU requested the NAS-NRC to establish a U. S. National Committee for the Third Geophysical Year in order to effect participation of the United States in the proposed geophysical year. The Chairman of NRC, after consulting the U. S. National Committees of the International Unions concerned, formed the following Committee: J. Kaplan (Chairman), Institute of Geophysics, University of California, Los Angeles, Calif.; L. H. Adams, Carnegie Institution of Washington, Washington, D. C.; H. G. Booker, Cornell University, School of Electrical Engineering, Ithaca, N. Y.; Lyman J. Briggs, 3208 Newark St., N. W., Washington, D. C.; G. M. Clemence, U. S. Naval Observatory, Washington, D. C.; C. T. Elvey, Geophysical Institute, College, Alaska; John A. Fleming, Carnegie Institution of Washington, Washington, D. C.; Nathaniel C. Gerson, Geophysics Research Directorate, Air Force Cambridge Research Center, Cambridge, Mass.; Paul Klopsteg, National Science Foundation, Washington, D. C.; F. W. Reichelderfer, U. S. Weather Bureau, Washington, D. C.; Elliott B. Roberts, U. S. Coast and Geodetic Survey, Washington, D. C.; Alan H. Shapley, National Bureau of Standards, Washington, D. C.; Paul A. Siple, Department of the Army, Washington, D. C.; Otto Struve, University of California, Berkeley, Calif.; Merle Tuve, Carnegie Institution of Washington, Washington, D. C.; and A. L. Washburn, Hanover, New Hampshire; with ex-officio members, Wallace W. Atwood, Jr., Office of International Relations, National Academy of Sciences, Washington, D. C.; Lloyd V. Berkner, Associated Universities, Inc., New York, N. Y.; J. Wallace Joyce, U. S. Department of State, Washington, D. C.; and Wm. W. Rubey, National Research Council, Washington, D. C.

Program suggestions from this committee were desired not later than May 15, 1953, in anticipation of the meeting of the International Committee scheduled for early July 1953. Accordingly, a meeting was held March 26-27, 1953, for study of its functions and to begin work upon the formulation of a program. The Committee elected A. H. Shapley, Vice-Chairman, and N. C. Gerson, Secretary.

Working groups were assigned duties of drawing up tentative programs in the various fields and of investigating sources of funds.

The Committee met again on May 1, 1953, when detailed proposals from the working groups were reviewed. Subcommittees of the U. S. National Committee were created to insure proper coordination of the work across the various disciplines: Arctic establishments, A. L. Washburn; Antarctic establishments, N. C. Gerson; Equatorial meteorology, H. Riehl; and Instrumentation, P.

Klopsteg. Each sub-committee is to be composed of qualified members within or without the U. S. National Committee.

E. B. Roberts

APPENDIX 4--REPORT OF THE COMMITTEE ON MEETINGS

John Putnam Marble, Chairman

Woodrow C. Jacobs
Herbert S. Riesbol
Walter E. A. Ruska
Glen E. Stout
Frank J. Veihmeyer

Since our last report, three meetings of the Union or of some of its Sections have been held.

(1) A meeting attended by members of various Sections at St. Louis in December, 1952, under the auspices of the American Association for the Advancement of Science, jointly with the American Meteorological Society. An interesting lot of papers was presented at two sessions, but the attendance was small, partly because of the press of other meetings and partly because the list of papers for the first session was not submitted in time for inclusion in the printed program.

(2) The Twenty-Ninth Regional Meeting at Stanford University, California, in February, 1953, in which two Sections took part. There was a good attendance and a full program was presented.

(3) The Thirty-Fourth Annual Meeting at Washington, D. C., on May 4-6, 1953. All Sections presented programs. There was a Symposium on the Earth's Interior, occupying two sessions; a lecture on recent oceanographic work in the Pacific, the Bowie Medal award, and the usual social events.

Plans for the Thirtieth Regional Meeting to be held in Minneapolis on August 31, 1953, have advanced to the point where a preliminary program has been prepared. This will shortly be sent to members of interested Sections.

The Union has been asked if it will take part in the meeting of the AAAS in Boston at the end of 1953. The Committee on Meetings plans to sound out the views of the members in the New England area, and asks for an expression of opinion from the Executive Committee.

As it is necessary to make arrangements for meeting rooms and other facilities at the earliest possible date, the Committee has taken upon itself, as its last job of the triennium, to set May 3-5, 1954, as the dates for the Thirty-Fifth Annual Meeting (Monday, Tuesday, and Wednesday, immediately following the sessions of the National Academy of Sciences). This follows the custom of recent years, and appears to be reasonably convenient for our membership.

APPENDIX 5--REPORT OF THE COMMITTEE ON BUDGET FOR THE FISCAL YEAR ENDING JUNE 30, 1954

Herbert N. Eaton, Chairman

Jno. A. Fleming
Nathan C. Grover
H. W. Hemple
Waldo L. Schmitt

The Committee on Budget of the American Geophysical Union has conferred with the General and Executive Secretaries of the Union regarding the budget for the fiscal year July 1, 1953, to June 30, 1954, and proposes the following budget. A probable small excess of receipts over expenditures is indicated, and as usual, the actual excess will probably be somewhat larger than that indicated since the Committee always attempts to overestimate expenditures and underestimate receipts slightly in order to provide a factor of safety. The excess of receipts over expenditures for the past year will probably be about $3000, instead of the $600 estimated in the last budget. Consequently, the Committee on Budget has not allowed as large a factor of safety in the present budget as it has done in recent years.

Operating Statement

Estimated receipts:			
National Research Council grant		$ 400	
Income:			
Dues: 20 corporation members, 4700 individual members, 1 life member	$35,000		
Sales, *Transactions*	6,600		
Sales, reprints	2,400		
Miscellaneous	200		
Interest on investments	200	44,400	
Total receipts			$44,800
Estimated expenditures:			
Publication of *Transactions*:			
Printing	$10,000		
Preparation	9,500[a]		
Mailing	1,000		
Co-editors	1,500	$22,000	
Reprints		2,200	
General office expenses:			
Salaries	$15,050		
Social Security	235		
Stationery and supplies	1,000		
Postage and communications	1,200		
Equipment	200	17,685	
Expenses, meetings:			
Annual	$ 700		
Regional	200	900	
Expenses, Sections		100	
Expenses, Committees		400	
Travel of officers		150	
Miscellaneous, including Bowie medal		50	
Transfer to Reserve, Directory		900	
Total expenditures			$44,385
Estimated excess of receipts over expenditures			415

[a] $100 of this is for supplies.

Transfer of Funds - 1954

Transfer from Cash Reserve to Reserve, Directory	$ 900

Statement of Assets as of June 30, 1953 and 1954 (estimated)

	1953		Changes		1954
General Funds:					
Cash reserve	$17,290		+$415 from operations	$17,705	
Directory	......		+ 900 from operations	900	
Horton Fund	1,180	$18,470	None	1,180	$19,785
Permanent Fund:					
U. S. Bonds (cost)	$ 2,368		None	$ 2,368	
Savings deposits	6,482	8,850	None	6,482	8,850
Emergency Fund		1,010	None		1,010
Bills Receivable less Bills Payable		2,500	None		2,500
Totals		$30,830			$32,145

The salary roll totals $24,750, of which $9,400 will apply to preparation of the *Transactions*, $15,050 to general office expense, and $300 to mailing the *Transactions*. (The Committee recommended and the Executive Committee approved certain salary increases that have been made a matter of record in the office of the Union.--Ed.)

The Committee also recommends that the officers of the Union on whose signatures the funds of the Union are drawn be bonded. In view of the large sums of money that they are now called upon to disburse, this seems to be an obvious precaution that should not be neglected.

In its last budget report, the Committee recommended that a line "Contributions" be added to the bills for dues. This recommendation was carried out, and an appreciable response has resulted from this suggestion to the members of the Union.

APPENDIX 6--SPECIAL REPORT OF THE COMMITTEE ON AUDIT REGARDING FISCAL PROCEDURES

R. H. Weightman, Chairman

A. G. McNish A. Nelson Sayre

Your Committee on Audit, in continuance of its report to the Executive Committee on November 7, 1952, as published in the December, 1952, Transactions, page 941, has made further study of the accounting and fiscal procedures employed in the Executive Office of the American Geophysical Union.

The Committee met with the General Secretary and the Executive Secretary and discussed such procedures in the light of Dr. J. A. Fleming's letter of suggestions. Since that time the subject has been given further consideration. Your Committee believes and this belief has the concurrence of the General Secretary that, with certain changes in procedures which have been effected through instructions issued by the General Secretary, all of the essential features of Dr. Fleming's suggestions have been adopted.

Procedures for the drawing and signing of checks have been modified and additional ledger accounts have been set up. A daily check of receipts and expenditures against bank balances, as shown by check stubs and bank statements, appears to impose additional work on an office force already worked to capacity for which there is not a sufficiently adequate return. A check of this kind is made as a routine matter at the end of each month and, if a special check is required between monthly checks, a special one can easily be made.

Your Committee does not feel that it is sufficiently familiar with the detailed workings of the office to attempt to draft complete instructions for working procedures for the guidance of the Executive Office which would, all circumstances considered, be an improvement of those already issued by the General Secretary.

In making the annual report, we believe that everyone will agree that the cost of the Transactions and of the Office should be as realistic as possible, especially as this is essential to the work of the Committee on Budget. To accomplish this, it is recommended that items, such as salaries, printing, mailing, etc., be split under their respective headings, specifying separately the amounts expended for the Transactions and for the office.

In conclusion, it is perhaps unnecessary to state that there has never been any question regarding the accuracy of the records. The changes inaugurated have been dictated entirely by a desire to make the procedures more in accord with standard practice, bearing in mind, however, the desirability of not increasing the office force.

APPENDIX 7--REPORT OF THE SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS FOR THE YEAR ENDING JUNE 30, 1953

Harlan T. Stetson, Chairman
E. O. Hulburt, Vice Chairman

Horace R. Byers Serge A. Korff W. T. Thom, Jr.
Ross Gunn Robert R. McMath George P. Woollard

Developments and investigations during the year in the region of the upper atmosphere, solar research, meteorology, radionics, and other allied fields have continued to call attention to the interrelated problems in Cosmic-Terrestrial Relationships which it is the object of this Special Committee to promote. Not only have the members of the Committee themselves contributed significantly during the year, but reports have been received from various other workers from whom the Committee has had active cooperation.

Sunspot activity has steadily decreased during the past year from an index of around 40 in July, 1952, to a low value of less than four in the early part of 1953. Many days in succession the solar disk has been clear of spots, characteristic of a near approach to the minimum of the cycle. Any indication of renewed activity in zones of high latitude would indicate the beginning of the next cycle of sunspots.

The Department of Terrestrial Magnetism of the Carnegie Institution of Washington has, as usual, made notable advances in various fields. These have included investigations of the Earth's crust involving seismic explosions, isotope dating of ancient sediments and igneous intrusives, the magnetization of rocks, ionospheric researches of the upper atmosphere, and cosmic-ray research. An extensive summary of many of these interrelated investigations is to be found in the current report of the Director and need not be detailed here.

E. O. Hulbert, Vice Chairman of the Committee (Director of Research of the Naval Research Laboratory), reports on upper atmospheric and solar research as follows:

Upper atmosphere rocket work--Final analyses of several propagation measurements in the ionosphere made with the aid of V-2 rockets were completed. By determining the ordinary and extraordinary indices of refraction in the neighborhood of the rocket it was established that, during the flight of a V-2 launched at 09h 58m MST on September 29, 1949, there existed an ion layer with a maximum of 5×10^8 ions/cc, a small electron layer with a maximum of 7500 electrons/cc just below the E_1-layer, and that the E_1-layer remained dense up to the E_2-layer. In contrast, the density apparently decreased above the E_1-layer maximum to much lower values at 13h 14m MST on January 22, 1948. A measurement of the Earth's magnetic field made during the September, 1949, flight at 105 km altitude was found to agree with the inverse cube law. The results of the flight also showed that the Lorentz polarization term should not be used in the E-layers at four megacycles [J. C. SEDDON, to be published in J. Geophys. Res.].

An analysis of a rocket measurement of the ionization spectrum of charged cosmic rays at latitude 41°N was completed. It was found that the ratio of protons to alpha particles in the primary radiation is 5.3/1.0.

A radio-frequency mass spectrometer was used to measure atmospheric composition between 95 and 135 km altitude during an Aerobee flight on February 12, 1953. It is believed that the data will show whether or not diffusive separation exists in this atmospheric region.

Additional solar ultraviolet spectra from rockets were secured, providing some increase in resolution over earlier spectra. An especially good exposure of the MgII $3s\,^2S-3p\,^2P^o$ doublet was secured in September, 1952 [F. S. JOHNSON, J. D. PURCELL, R. TOUSEY, and N. WILSON, Astrophys. J., v. 117, pp. 238-239, 1953]. The diurnal heating effect in the upper atmosphere, due to absorption of solar energy by ozone, was computed from ozone distribution and solar-energy distribution data obtained from a rocket flight in June, 1947 [F. S. JOHNSON, Bull. Amer. Met. Soc., v. 34, pp. 106-110, 1953]. Measurements with photon counters gave quantitative information on the amounts of energy in, and penetration into the atmosphere of, soft x-rays and Hydrogen Lyman alpha radiation [E. T. BYRAM, T. CHUBB, H. FRIEDMAN, and S. W. LICHTMAN, J. Opt. Soc. Amer., v. 42, p. 876, 1952].

Cosmic-ray research--Systematic studies of high-energy nucleon-nucleon collisions have been carried out in thick nuclear emulsions exposed to the cosmic radiation in balloon flights in Minnesota at altitudes of 100,000 ft. Among events which have been observed involving the production of heavier-than-π charged mesons, five are of exceptional interest; three provide a precise estimate for the mass of K particles, 1270-1290m_e; and the other two constitute the first supporting evidence for the probable existence of charged "zetz" mesons of approximately twice pion mass [D. T. KING, N. SEEMAN, and M. M. SHAPIRO, to be published in Phys. Rev.].

Radio astronomy--The 50-ft radio telescope has been in use for several months. Pattern measurements at three-cm and eight-mm wavelength have revealed that the surface tolerance of the reflector is up to expectations, the pattern at eight mm yielding a beam width of three to four minutes of arc. Drift curves of the Sun and Moon have been made yielding a radial brightness distribution curve. The interpretation of these curves is being applied to a refinement of the theory of the structure of the Sun's atmosphere and its effect on the origin of the radio radiation. The radial brightness distribution measurements are of sufficient resolution to reveal the location of the excess radiation associated with spot activity. The progress of localized active regions is observed across the disk of the Sun.

Some work has been done on the measurement of outbursts associated with chromospheric flares. These have in the past been observed at longer wavelengths and now have been observed for the first time at eight-mm wavelengths [J. P. HAGEN and N. HEPBURN, Nature, v. 170, pp. 244, 1952]. Simultaneous observations at eight-mm and longer wavelengths are being made to determine the nature and origin of the disturbance giving rise to the outburst.

Solar eclipse--The total eclipse of the Sun on February 25, 1952, was observed near Khartoum, Sudan, by a party from the Naval Research Laboratory. In order to determine the kinetic temperature and pressure in the chromosphere, triple spectra of the chromospheric flash were made and the solar radio emissions at wavelengths of 9.4 cm and 8.5 mm during the entire eclipse were measured. The radio wavelengths were chosen because they originated in the chromosphere. The radio eclipse curves thus obtained were compared with eclipse curves deduced from various models of the solar chromosphere. Preliminary results from the 9.4-cm wavelength data agreed in general with the eclipse curve deduced from a model of the chromosphere wherein the kinetic temperatures of the lower chromosphere is the coolest [J. P. HAGEN and Others, to be published in Astrophys. J.].

Spectra were taken every 3/4 second of the light from the solar crescents near second and third contacts. From these the darkening of the Sun near the limb was determined over the outer one per cent of the solar radius for wavelengths from 3800 to 5800 A; the spectral intensity throughout this wavelength interval was also determined near the limb. The solar limb darkening over the outer 0.1 per cent for a wavelength band from 7000 to 9000 A was measured with a photocell [F. J. HEYDEN and Others, to be published in Astrophys. J.].

Robert R. McMath (McMath-Hulbert Observatory of the University of Michigan) reports as follows:

At the McMath-Hulbert Observatory of the University of Michigan the program of observation and analysis of the solar spectrum with high dispersion continues. Wavelengths and intensities have been determined for more than 6400 lines in the spectral region between $\lambda 12,950$ and $\lambda 25,578$. About 4500 of these lines have been identified as due to specific atomic or molecular constituents in the solar or terrestrial atmospheres. Carbon monoxide was positively identified as present in the solar atmospheres. Numerous studies of the laboratory spectra of CO, CO_2, CH_4, N_2O, and H_2O have been carried out to assist in the above identifications and to permit determination of the abundance of these molecules in the atmospheres of the Sun and Earth. A new determination of the relative energy distribution in the solar spectrum is in progress. Observations for the above studies have been made in part at Lake Angelus and in part with our infrared spectrograph attached to the Snow telescope at Mount Wilson.

As in preceding years, continuous monochromatic, photographic studies of rapidly changing solar activity have formed part of the regular program of the Observatory. Spectroheliographic records of the disk in $H\alpha$ and the K line of ionized calcium show the development of plage areas and sunspot regions, the growth and activity of the dark flocculi, and the outbreak of flares. Combined limb and disk observations have indicated that certain active prominences with relatively short lifetimes (30 min ±) appear bright, rather than dark, when observed in projection against the solar disk. The intensity of these prominences, bright in projection against the disk, was comparable to that of the hydrogen plages and much less than that of flares.

The study of flares has been continued. More photometric light curves have been determined and analyzed. The flare data have been compared with concomitant radiations at 200 Mc/s (Cornell) and 2800 Mc/s (National Research Council, Ottawa). Observations, principally with the Stone radial velocity spectroheliograph, have shown that there is an ejection of hydrogen and ionized calcium atoms with high velocity at the onset of certain solar flares. Distinctive bursts occurred on radio frequencies at the start of the high-velocity ejections.

Charts containing solar, ionospheric, and geomagnetic data have been kept up to date and assist in the study of solar regions associated with terrestrial disturbances.

Donald B. Menzel, speaking for the activities of the Harvard Observatory, communicates:

John W. Evans and I have greatly refined the methods of classifying solar prominences and the first detailed report on this classification will appear in the Proceedings of the Convegno Volta, which will shortly be published in Arcetri, Italy. At Harvard, Max Krook, R. N. Thomas, and I have been continuing studies of magnetohydrodynamics. We have been making satisfactory progress in the development of a model of solar prominences, in which the filamentary structure represents a system of electric currents produced by the flow of conducting matter in the magnetic field of the Sun and sunspots.

Further studies of the aurora borealis, with the aid of magnetohydrodynamics, has led to refinement of the theory reported on in the minutes of the meeting last year.

S. A. Korff of New York University has continued his researches in the field of cosmic rays for which he provides this summary:

Investigation of cosmic-ray neutrons has continued. During July and August, 1952, a series of balloon flights was conducted to high elevations at far northern latitudes. The flights were made off Greenland, at geomagnetic latitude 89°. Neutron counters were operated at elevations up to 90,000 ft. The resulting data show that neutron intensities in the far northern latitudes are not much greater than in Minnesota, geomagnetic latitude 55°. The observations suggest that not much new radiation comes in, with primary energy less than two Bev (billion electron volts). The exact amounts are at present being evaluated. The primary spectrum of the cosmic radiation shows a marked drop to quite low values below two Bev. The probable interpretation of this effect is to be found in the absorption of cosmic-ray particles by galactic material, the energy loss being large for particles below the two-Bev energy.

A continuously operating neutron monitor has been installed at Fairbanks, Alaska, and will be used to record fluctuations, which will be studied for correlation with solar disturbances.

A. Beiser of our staff derived an expression for the luminosity of an auroral arc as a function of its depth in the atmosphere using the theories of Chapman. The expression appears to give good agreement with observed values.

H. R. Byers, speaking for the field of Meteorology, states:

Interest in cosmic-terrestrial relationships involving the weather were stimulated by the reporting in 1952 by the German meteorologist, R. Scherhag, of unusual temperature changes in the high atmosphere. The results were reported in an article entitled Die explosionsartigen Stratosphärenerwärmungen des Spätwinters 1951/1952 published in Berichte des Deutschen Wetterdienstes in der US-Zone, no. 38, pp. 51-63. In January, February, and March, 1952, the radiosonde observations at Berlin showed some sudden stratosphere temperature rises amounting to 30° to 50° C in a few days time at heights above 30,000 m. These temperature changes subsequently worked down to lower levels. Scherhag concluded that the changes were related to solar eruptions, and made a statistical correlation between the figures of daily magnetic activity and the temperature in the upper stratosphere which appeared to prove the relation.

In the Journal of Meteorology [v. 10, pp. 1-9, Feb., 1953], C. E. PALMER presented a paper entitled The Impulsive Generation of Certain Changes in the Tropospheric Circulation. He also presented data for tropical regions showing a sudden rise of temperature in the various layers of the stratosphere. He reported on various soundings in the Marshall Islands showing temperature increases at around 20 km as well as at the higher layers reported by Scherhag in the Berlin observations. These sudden temperature rises, he believes, are due to solar flares. The author presents evidence suggesting that high-level tropical cyclones originate in response to these sudden increases.

In another article in the Journal of Meteorology [v. 9, pp. 126-138, April 1952], RICHARD A. CRAIG, writing on Surface-Pressure Variations Following Geomagnetically Disturbed and Geomagnetically Quiet Days, finds a marked negative correlation between the surface pressure variations under the two types of conditions. He concludes that there is a link between the phenomena in the ionosphere and troposphere. W. KACIAK and P. LANGWELL, in a paper entitled Relation between Geomagnetic Activity and Pressure Variations Aloft [J. Met., v. 9, pp. 409-414, Dec., 1952], reported on a somewhat similar study of pressure variations in the middle and upper troposphere. They found that the greatest number of statistically significant pressure variations at these heights occur on the third through the sixth days following the geomagnetically quiet days. The effect is especially pronounced at and north of the latitude 60°N.

The Scherhag and similar results were discussed in papers before the American Meteorological Society by B. Haurwitz at the January, 1953, meeting in New York and H. C. Willett at the March, 1953, meeting in Atlantic City. Both contributors indicated that the temperature changes could not be accounted for by transport of air either horizontally or vertically from some other region or altitude. While Palmer in his paper attributed the heating to absorption of ultraviolet radiation by water vapor, Willett expressed the view that corpuscular radiations of the type described by Menzel might be responsible although no precise radiative transfer mechanism could be described. Since this corpuscular radiation comes into the Earth's atmosphere along the magnetic lines of force, it was conceded that this effect could not account for temperature increases in the tropical stratosphere.

In last year's report of this Committee the opposing views represented largely by the work of Jerome Namias were mentioned. Namias believes that the atmosphere has within itself the possibility of producing marked changes according to his "self-developmental" hypothesis. In a paper in the Bulletin of the American Meteorological Society [v. 33, pp. 279-286, Sep., 1952] entitled The Annual Course of Month-to-Month Persistence in Climatic Anomalies, Namias finds a tendency for persistence in various meteorological elements during all adjacent pairs of months except from April to May and from October to November when great and often abrupt transitions of long-period regimes occur. He contends that the changes in large-scale patterns of the general circulation accompany the maximum variation of insolation occurring in the transition seasons. He points out that the location and strength of important heat sources and sinks near the Earth's surface change at these times of the year, and this tends to produce changes in pressure pattern. He admits that an analysis of the year-to-year behavior of persistence suggests possible gradual secular trends which might be related to sunspots, but he finds the evidence to be inconclusive.

The Chairman takes this occasion to make acknowledgment of the courtesies of the U. S. Weather Bureau, both at Washington and at the Jacksonville Station, in supplying back meteorological data pertinent to possible long-term trends in Florida weather. Investigations of over 200 hurricanes originating in the Caribbean area have thus far indicated a possible inverse relationship to the solar cycle. This is in agreement with Clayton's investigation of hurricanes in the South Pacific Ocean, and opposite to the effect found by Clayton in the Indian Ocean. A more complete report may be anticipated on completion of the investigation now in progress.

ANNUAL REPORT OF THE PACIFIC SOUTHWEST BRANCH, AGU

The Pacific Southwest Region held one meeting in 1953. This was at Stanford University, California, on February 6 and 7 with the Sections of Hydrology and Meteorology participating. This meeting was reported briefly in the Transactions for June, 1953, page 510.

Plans for a regional meeting in 1954 have progressed satisfactorily. The University of Southern California, Departments of Civil Engineering and Geology, have offered to sponsor a meeting to be held in January, with January 29 and 30 as suggested dates. This offer has been tentatively accepted subject to final approval of the new Regional Committee which will take office on July 1, 1953.

The Pacific Southwest Region completes its first triennium as an organized Region of the Union on June 30, 1953. During this time, three annual meetings have been held and the Region has, we feel, become well established. A large share of credit for this should go to our Committee Chairman, J. W. Johnson, and also to Frank J. Veihmeyer, President of the Section of Hydrology, who was instrumental in engineering the initial formation of the Region.

A new Regional Committee has been elected to serve during the triennium beginning July 1, 1953. This new Committee has held its first meeting and has elected as its Chairman, Martin R. Huberty, Professor of Irrigation, University of California at Los Angeles; and as its secretary, Mr. R. Corday Counts, Jr., Supervising District Forecaster, U. S. Weather Bureau, San Bruno, California.

EDWARD M. VERNON, Secretary
Pacific Southwest Regional Committee, AGU

SPECIAL ANNOUNCEMENTS

Changes of Address--A new policy put into effect by the Post Office Department has resulted in the destruction of most of the copies of the June issue of the Transactions sent to those whose addresses had been changed but who had not informed us. The new policy means, also, that those copies returned because of wrong address will involve much higher "postage due" charges than hitherto. We, therefore, urge that all members and subscribers advise us promptly of any changes of address. Changes are usually made in our mailing list about the tenth of the even-numbered (Feb., Apr., etc.) months, and changes anticipated before the end of those months should be sent by the tenth. Send these to the office of AGU at 1530 P St., N. W., Washington 5, D. C.

Meeting of the AAAS in Boston, December 26-31, 1953--The American Geophysical Union, as an affiliate of the AAAS, has been asked, as usual, to join in the Association's meeting in Boston between Christmas and New Year's. Plans at the time of going to press are uncertain. See SPECIAL ANNOUNCEMENTS in the October issue for further word on this, or write to the office of the Union at 1530 P St., N. W., Washington 5, D. C.

Meeting in California--No details have yet been received concerning the meeting in Los Angeles, California, in January, 1954, beyond those published in the June, 1953, issue of the Transactions, page 510. The Regional Committee has organized, with Martin R. Huberty (Professor of Irrigation, University of California, Los Angeles, Calif.) as Chairman, and R. Corday Counts, Jr. (Supervising District Forecaster, U. S. Weather Bureau, San Bruno, California) as Secretary. Persons interested in the meeting should get into touch with one of these, or with the members of the Local Committee (Stanley S. Butler and John Mann at the University of Southern California).

Thirty-Fifth Annual Meeting, Washington, D. C., May 3-5, 1954--Attention is called to the preliminary announcement in the June issue of the Transactions [p. 510] giving the dates for the Thirty-Fifth Annual Meeting (as shown above), issuing the first call for titles and abstracts of papers, and requesting suggestions. Watch the SPECIAL ANNOUNCEMENTS in October for more details.

Tenth General Assembly of the IUGG in Rome, Italy, September 15-29, 1954--The Tenth General Assembly of the International Union of Geodesy and Geophysics (of which AGU is the USA National Committee) and its seven associations will meet in Rome, Italy, September 15-29, 1954. Members of the AGU and their guests are welcome to attend and otherwise take part. Send word of interest or plans to attend to the office of AGU, 1530 P St., N. W., Washington 5, D. C., as promptly as possible in order that they may be kept informed of developments. At the Ninth General Assembly in Brussels in 1951, about 125 attended from the United States [see Oct., 1951, pp. 785-788]. Watch SPECIAL ANNOUNCEMENTS for further information.

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A PROPOSED TECHNIQUE FOR REDUCTION OF SHORAN DATA TO GEODETIC DISTANCES

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Abstract--Formulas adapted to the rapid slide-rule computation of the difference, geodetic distance minus shoran measurement, are developed, and numerical examples are given. The method offers adequate accuracy and adequate control of accuracy for all shoran reductions, eliminating a serious source of non-random error in the reduction of line-crossings by the conventional Canadian method. The effects of errors in the data, particularly those in the meteorological data, are considered.

Introduction--In recent years the use of shoran for geodetic measurements has permitted the rapid surveying of vast expanses of relatively inaccessible areas. Briefly, the method consists of measuring the time required for a radar wave to travel from an airborne station to a ground station. From meteorological data, the variation of the index of refraction with height can be determined, and thus the elapsed time can be converted to a ray-path length. Knowledge of the heights of the airborne and ground stations above mean sea level permits the evaluation of the mean sea-level distance between the two stations.

In order to reduce the shoran data rapidly, it has been customary in Canada [ROSS, 1951] to assume that the ray path is an arc of a circle. The arc is divided into segments of equal-height intervals, for each of which a correction (based on indices of refraction) is computed to convert the arc-segment length to an element of mean sea-level distance. In general, this technique will be satisfactory, especially if the index of refraction changes smoothly with height. If the variation is not regular, significant errors may be introduced by this method of calculation [KROLL, 1949]. Accordingly, it was felt advisable to develop a method of computation relatively free from assumptions, yet simple to apply and not too time-consuming. Such a method is outlined below, and was first employed in the field during the summer months of 1952.

Basic theory of method--The fundamentals of the geometry of the ray path are illustrated by Figure 1. A represents the ground station at an elevation Z_0 above mean sea level, and B represents the airborne station at an elevation Z_m above mean sea level. β represents the elevation

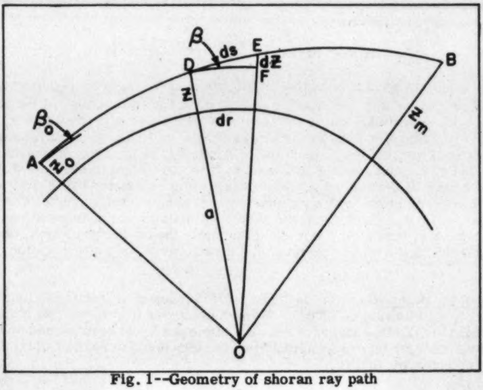

Fig. 1--Geometry of shoran ray path

angle of the ray path at any point, a the Earth's radius, s distance along the ray path, and r distance at mean sea level.

For a stratified atmosphere, Snell's law takes on the form [KROLL, 1949]

$$N \cos \beta = N_0 \cos \beta_0 = C \quad \ldots\ldots (1)$$

where C is a constant and N represents the modified index of refraction. Thus

$$N = n\,(1 + z/a) \quad \ldots\ldots (2)$$

where n is the index of refraction.

Referring to triangle DEF in Figure 1, it can be seen that

$$\tan \beta = (N^2 - C^2)^{1/2}/C = a\,dz/(a + z)\,dr$$

Hence

$$dr = C\,dz/[(1 + z/a)\,(N^2 - C^2)^{1/2}] \quad \ldots\ldots (3)$$

Moreover

$$\sin \beta = (N^2 - C^2)^{1/2}/N = dz/ds$$

Thus

$$ds = N\,dz/(N^2 - C^2)^{1/2} \quad \ldots\ldots (4)$$

The velocity of the radar waves, c, is given as

$$c = ds/dt = c_0/n \quad \ldots\ldots (5)$$

where c_0 represents the velocity in a vacuum.

Although the shoran set measures an element of time, the numerical presentation of this information is in terms of the distance, under standard conditions, along the ray path. The set is calibrated assuming a constant index of refraction, n_s, the value at S.T.P. (standard temperature and pressure). If this distance is denoted by x, it follows from (5) that

$$dx/dt = c_0/n_s \quad \ldots\ldots (6)$$

Combining (2), (4), (5), and (6) gives

$$dx = N^2\,dz/[n_s\,(1 + z/a)\,(N^2 - C^2)^{1/2}] \quad \ldots\ldots (7)$$

The shoran set gives a value of x, that is, of $\int dx$, and the quantity required is r, that is, $\int dr$. From (7) and (3), it can be seen that x and r depend upon known functions of height and upon the unknown parameter, C. Formally, one could assume a trial value of C, evaluate x, and then adjust C to give the observed value of x. Following this, a single set of integrations would give r. The technique can be rendered much more elegant and accurate by the following procedure. Since the difference between r and x is much smaller than r or x, it is convenient to evaluate directly this difference, r - x, which may be denoted by y. Moreover, if y is calculated using the initial trial value of C, it is possible to adjust this value automatically for the correct value of C without a second integration for x (or for y). Thus, from the results of a single set of integrations for x and a single set of integrations for y, it is possible to obtain directly the correction which, when applied to the S.T.P. path length, gives the mean sea-level distance between the ground station and the airborne station.

Integration of equations--In practice, the modified index of refraction is known at discrete levels only, usually at intervals of 1000 ft. In most instances it is found that N varies linearly with height over relatively deep layers. Thus the atmosphere between ground and airborne stations can be divided into discrete layers (generally two is sufficient), in each of which the lapse rate of N may be assumed constant, that is,

$$N = N_n + \alpha_n (z - z_n) \qquad n = 0, 1, \ldots m \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

The quantities N, C, n_s, and $(1 + z/a)$ are all very nearly unity, so that squares and products of $(N - 1)$, $(C - 1)$, $(n_s - 1)$, and z/a can be neglected (possible errors due to this assumption will be discussed later). Set

$$N_n = 1 + \gamma_n \qquad C = 1 + \mu \qquad n_s = 1 + \sigma \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

From the above assumption it follows that

$$N_n^2 = 1 + 2\,\gamma_n \qquad C^2 = 1 + 2\mu \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Let Δx be the contribution to x from the layer z_n to z_{n+1}. From (7)

$$\left.\begin{aligned} n_s\Delta x &= 2^{-1/2}\int_{z_n}^{z_{n+1}} [\{1 + 2\,\gamma_n + 2\alpha_n (z - z_n)\}\,dz]/[\{1 + z_n/a + (z - z_n)/a\}\{\gamma_n - \mu + \alpha_n (z - z_n)\}^{1/2}] \\ n_s\Delta x &= 2^{-1/2}\int_{0}^{z_{n+1}-z_n} [\{1 + 2\gamma_n - z_n/a + (2\alpha_n - 1/a)(z - z_n)\}\,d\,(z - z_n)]/[(\gamma_n - \mu) + \alpha_n (z - z_n)]^{1/2} \end{aligned}\right\} (11)$$

$$\begin{aligned} n_s\Delta x = {}& 2^{1/2}\,\alpha_n^{-1}\left\{(\gamma_{n+1} - \mu)^{1/2} - (\gamma_n - \mu)^{1/2}\right\}\{1 + 2\,(\gamma_n + 2\mu)/3 - z_n/a \\ & + 2\,(\gamma_n - \mu)/3a\,\alpha_n\} + 2^{1/2}\,(\gamma_{n+1} - \mu)^{1/2}\,(2 - 1/a\,\alpha_n)\,(z_{n+1} - z_n)/3 \quad \ldots\ldots (12) \end{aligned}$$

Let Δr be the contribution to r from the layer z_n to z_{n+1}. From (3)

$$n_s\Delta r = 2^{-1/2}\int_{0}^{z_{n+1}-z_n} [\{1 + \mu + \sigma - z_n/a - (z - z_n)/a\}\,d\,(z - z_n)]/[(\gamma_n - \mu) + \alpha_n (z - z_n)]^{1/2} \quad .. (13)$$

$$\begin{aligned} n_s\Delta r = {}& 2^{1/2}\,\alpha_n^{-1}\left\{(\gamma_{n+1} - \mu)^{1/2} - (\gamma_n - \mu)^{1/2}\right\}\left\{1 + \mu + \sigma - z_n/a + 2\,(\gamma_n - \mu)/3a\,\alpha_n\right\} \\ & - 2^{1/2}\,(\gamma_{n+1} - \mu)^{1/2}\,(z_{n+1} - z_n)/3a\,\alpha_n \quad \ldots\ldots\ldots\ldots\ldots\ldots (14) \end{aligned}$$

From (12) and (14), the contribution to y is

$$\begin{aligned} n_s\Delta y = {}& 2^{1/2}\,\alpha_n^{-1}\left\{(\gamma_{n+1} - \mu)^{1/2} - (\gamma_n - \mu)^{1/2}\right\}(3\sigma - \mu - 2\,\gamma_n)/3 \\ & - 2^{3/2}\,(\gamma_{n+1} - \mu)^{1/2}\,(z_{n+1} - z_n)/3 \quad \ldots\ldots\ldots\ldots\ldots\ldots (15) \end{aligned}$$

Neglecting the very small terms in (12), and substituting for α_n from (8) and (9), gives

$$\Delta x = 2^{1/2}\,(z_{n+1} - z_n)/[(\gamma_{n+1} - \mu)^{1/2} + (\gamma_n - \mu)^{1/2}] \quad \ldots\ldots\ldots\ldots (16)$$

With a similar substitution, and after simplification, (15) can be put into the form

$$\Delta y = -\,(2\,\Delta x/3)\left\{(\gamma_{n+1} - \mu) + (\gamma_n - \mu) + (\gamma_{n+1} - \mu)^{1/2}\,(\gamma_n - \mu)^{1/2} - 3\,(\sigma - \mu)/2\right\} \quad \ldots (17)$$

The first step in the procedure is the adoption of a trial value for μ, say μ_o. If (16) is applied to the entire atmosphere from z_o to z_m, it follows that

$$x = 2^{1/2}\,(z_m - z_o)/[(\gamma_m - \mu_o)^{1/2} + (\gamma_o - \mu_o)^{1/2}] \quad \ldots\ldots\ldots\ldots (18)$$

where x represents the shoran-measured ray-path length. Solving (18) for μ_o, and setting $z = z_m - z_o$

$$\mu_o = (\gamma_o + \gamma_m)/2 - z^2/2\,x^2 - \left\{(\gamma_m - \gamma_o)\,x/z\right\}^2/8 \quad \ldots\ldots\ldots\ldots (19)$$

Intuition suggests that a slightly better choice of μ_o, taking into account the distribution of γ with height, would be

$$\mu_o = \bar{\gamma} - z^2/2\,x^2 - \left\{(\gamma_m - \gamma_o)\,x/z\right\}^2/8 \tag{20}$$

where $\bar{\gamma}$ is a mean value of γ, weighted relative to height.

Adjustment of solutions--If μ_o is well chosen, use can be made of first-order Taylor expansions in order to obtain the actual values of μ and y, that is

$$x\,(\mu) = x\,(\mu_o) + (\partial x/\partial\mu)_o\,(\mu - \mu_o) \tag{21}$$

$$y\,(\mu) = y\,(\mu_o) + (\partial y/\partial\mu)_o\,(\mu - \mu_o) \tag{22}$$

Let $\Delta\,(\partial x/\partial\mu)$ be the contribution to $\partial x/\partial\mu$ from the layer z_n to z_{n+1}. Thus, from (11)

$$n_s\Delta\,(\partial x/\partial\mu) = 2^{-3/2}\int_o^{z_{n+1}-z_n}[\left\{1 + 2\gamma_n - z_n/a + (2\alpha_n - 1/a)(z - z_n)\right\}d\,(z - z_n)/ \\ [(\gamma_n - \mu) + \alpha_n\,(z - z_n)]^{3/2} \tag{23}$$

$$n_s\Delta\,(\partial x/\partial\mu) = (2^{1/2}\alpha_n)^{-1}\left\{(\gamma_{n+1} - \mu)^{-1/2} - (\gamma_n - \mu)^{-1/2}\right\}\left\{-1 + 2\,\gamma_n - 4\mu \right. \\ \left. + z_n/a - 2\,(\gamma_n - \mu)/a\,\alpha_n\right\} + (z_{n+1} - z_n)\,(2 - 1/a\alpha_n)\,(2\,\gamma_{n+1} - 2\,\mu)^{-1/2} \tag{24}$$

Let $\Delta\,(\partial r/\partial\mu)$ be the contribution to $\partial r/\partial\mu$ from the layer z_n to z_{n+1}. Thus, from (13)

$$n_s\Delta\,(\partial r/\partial\mu) = 2^{-1/2}\int_o^{z_{n+1}-z_n} d\,(z - z_n)/[(\gamma_n - \mu) + \alpha_n\,(z - z_n)]^{1/2} \\ + 2^{-3/2}\int_o^{z_{n+1}-z_n}[\left\{1 + \mu + \sigma - z_n/a - (z - z_n)/a\right\}d\,(z - z_n)]/ \\ [(\gamma_n - \mu) + \alpha_n\,(z - z_n)]^{3/2} \tag{25}$$

$$n_s\Delta\,(\partial r/\partial\mu) = 2^{1/2}\,\alpha_n^{-1}\left\{(\gamma_{n+1} - \mu)^{1/2} - (\gamma_n - \mu)^{1/2}\right\} \\ + (2^{1/2}\,\alpha_n)^{-1}\left\{(\gamma_{n+1} - \mu)^{-1/2} - (\gamma_n - \mu)^{-1/2}\right\}\left\{-1 - \mu - \sigma + z_n/a \right. \\ \left. - 2\,(\gamma_n - \mu)/a\alpha_n\right\} - (z_{n+1} - z_n)/a\alpha_n\,(2\,\gamma_{n+1} - 2\mu)^{1/2} \tag{26}$$

From (24) and (26)

$$n_s\Delta\,(\partial y/\partial\mu) = 2^{1/2}\,\alpha_n^{-1}\left\{(\gamma_{n+1} - \mu)^{1/2} - (\gamma_n - \mu)^{1/2}\right\} \\ + (2^{1/2}\,\alpha_n)^{-1}\left\{(\gamma_{n+1} - \mu)^{-1/2} - (\gamma_n - \mu)^{-1/2}\right\} \\ (3\mu - \sigma - 2\,\gamma_n) - 2^{1/2}\,(z_{n+1} - z_n)\,(\gamma_{n+1} - \mu)^{-1/2} \tag{27}$$

Substituting for α_n in (24) and (27), and neglecting the small terms in (24)

$$\Delta\,(\partial x/\partial\mu) = \Delta x/[2\,(\gamma_{n+1} - \mu)^{1/2}\,(\gamma_n - \mu)^{1/2}] \tag{28}$$

$$\Delta\,(\partial y/\partial\mu) = (\sigma - \mu)\,\Delta\,(\partial x/\partial\mu) \tag{29}$$

From (21) and (22)

$$y\,(\mu) = y\,(\mu_o) + \left\{x\,(\mu) - x\,(\mu_o)\right\}(\partial y/\partial\mu)_o/(\partial x/\partial\mu)_o \tag{30}$$

Using (28) and (29), performing the required summations, and identifying x (μ) as the shoran measured x

$$y = r - x = \Sigma \Delta y\,(\mu_o) + (\sigma - \mu_o)\left\{x - \Sigma \Delta x\,(\mu_o)\right\} \quad \text{. . . . . (31)}$$

Thus in general only a single trial value of μ_o need be used, the above relation automatically adjusting y to the value appropriate to the correct μ. With a very abnormal distribution of N with height, it is possible that μ_o, as defined by (20), might be a poor choice and that a second trial value might be required. This will be illustrated by an artificial example to be presented later in this paper (Example 5, below).

Layer subdivision required--As mentioned earlier, sufficient accuracy is achieved, in most instances, by division of the atmosphere from ground station to airborne station into two layers. The number of layers required will be suggested by the plot of the modified index of refraction N against height.

The increase in accuracy achieved by subdivision can be estimated fairly simply. Let y′ denote the value of y obtained when the atmosphere is adequately stratified, except that the layers from z_n to z_{n+1} and z_{n+1} to z_{n+2} have been combined into a single layer. Let $\Delta x'$ denote the value of Δx for this combined layer, from z_n to z_{n+2}. It can be shown that the error produced by this layer combination is approximately

$$y - y' \approx \Delta x'\left\{(\gamma_n + \gamma_{n+2})/2 - \gamma_{n+1}\right\} \quad \text{. . . . . (32)}$$

The above relation can be used only to indicate when further subdivision is required. If $\Delta x'$ is of the order of 100 mi, $(\bar{\gamma} - \gamma)$ must be of the order of 10^{-6} if the error in y is to be no more than 10^{-4} mi. When the various possible sources of error arising from meteorological data are considered, it can be seen that an accuracy of 10^{-4} mi in mean sea-level distance is seldom achievable. Computational errors resulting from the mathematical simplifications adopted will almost invariably be less than 2×10^{-4} mi, even for distances of the order of 300 mi.

Practical limitations of accuracy--The accuracy of any shoran technique is limited by the accuracy of the meteorological data utilized. Such data include the heights of various pressure surfaces, and the temperature and relative humidity at those levels. Purely instrumental errors will not be discussed here, since their effects can be readily deduced. Thus, for example, a shoran error in x will be carried over to give the same error in map distance, pressure altitude errors (due to the aneroid altimeter) will have the same effect as the true altitude errors to be discussed below, and a temperature error of 1.0°C will directly cause an error in γ of the order of only 1×10^{-6}.

If the true elevation of the ground station is not known exactly, the use of an altitude determined barometrically will introduce a constant height error δz, say, at all pressure levels. Treating the atmosphere as a single layer, it follows that the error in y will be

$$\delta y = -\,x\,\delta z/a \quad \text{. . . . . (33)}$$

Thus, for a distance of 200 mi, an elevation error of 50 ft will produce a distance error of 0.0005 mi. Such errors are thus quite likely in irregular terrain, at points which are not close to meteorological stations of known elevation.

If the elevation of the ground station is assumed known, but the elevation of the aircraft is in error by δz, say, the resulting error in y can also be computed for the single layer problem if the height error is cumulative (non-random). In this case the result is

$$\delta y = [y - (\sigma - \mu)\,x]\,\delta z/z - [1 + (\gamma_o - \mu)^{1/2}/\left\{(\gamma_m - \mu)^{1/2} + (\gamma_o - \mu)^{1/2}\right\}]\,x\,\delta z/3a \quad \text{. . . (34)}$$

For a map distance of 200 mi, the first term is of the order of $-\,0.4\,\delta z/z$ mi, and the second term $-\,\delta z/40$ mi. If z is of the order of three to four miles, a height error of the aircraft (relative to the ground station) of 50 ft produces an error in geodetic distance of the order of 0.0015 mi. Such a relative height error could be caused by a mean temperature error of about 1°C, or by a direct altimeter error of the same magnitude (50 ft). It can be seen that the chief effect of a non-random temperature error is the height error produced, since a temperature error of 2°C at the mid-point of the sounding causes a distance error, from (32), for a 200-mi line, of only 0.0004 mi.

Since the aircraft elevation may be in error by 150-175 ft [ROSS, 1951], the resulting (or net) error in y due to height errors could exceed 0.005 mi. On averaging results from a number of line crossings, the above error will be reduced somewhat. Individual shoran path lengths (standard atmosphere) are subject to instrumental uncertainties of at least the same order. It may be concluded that the proposed technique, using very few layers, gives more than adequate computational accuracy, since a good circular slide rule yields the geodetic distance with a probable error of computation, assuming all data used accurate, of the order of 0.0001 mi. This accuracy is desirable, if non-random errors are to be kept to a minimum.

Examples of computation--The following four examples were taken from actual field measurements in northern Canada. The values of x and y apply to the leg from aircraft position to one ground station; 2r gives the mean sea-level distance between the two ground stations, assuming, for simplicity, identical conditions (topographic and meteorological) at the two stations. In evaluating $\bar{\gamma}$ (prior to obtaining μ_0) the layers were assigned small integral weights, since extreme accuracy was not required. Following ASLAKSON [1949], σ was set equal to 283.5×10^{-6}.

Example 1--Data and computations are as follows

z (ft)	$10^6\gamma$	$\mu_0 = 262 \times 10^{-6}$; x = 108.0197 mi
1,197	382	$\Sigma \Delta x = 107.84$ mi; $\Sigma \Delta y = -0.06825$ mi
6,000	523	y = -0.06825 mi; 2r = 215.9029 mi
15,365	906	Conventional: 2r = 215.9025 mi

It was estimated that the correction to y for neglected small terms was 0.56×10^{-4} mi. All computations were performed with a circular slide rule, which is ideally suited to the technique, in view of the order of accuracy of the data and the method.

Example 2--Data and computations are as follows

z (ft)	$10^6\gamma$	$\mu_0 = 218.5 \times 10^{-6}$; x = 107.4822 mi
1,538	383.0	$\Sigma \Delta x = 107.69$ mi; $\Sigma \Delta y = -0.08140$ mi
6,000	522.5	y = -0.08139 mi; 2r = 214.8016 mi
17,405	985.5	Conventional: 2r = 214.7997 mi

It was estimated that the correction to y for neglected small terms was 0.71×10^{-4} mi. In this case the conventional method of computation gave an error of about -0.002 mi, which would apply to all eight line crossings made at that time.

Example 3--Data and computations are as follows

z ft)	$10^6\gamma$	$\mu_0 = 318.0 \times 10^{-6}$; x = 160.0501 mi
664	328	$\Sigma \Delta x = 158.94$ mi; $\Sigma \Delta y = -0.09121$ mi
8,000	619	y = -0.09125 mi; 2r = 319.9177 mi
18,406	1034	Conventional: 2r = 319.9192 mi

In this case the small-term correction amounted to 0.86×10^{-4}, and the error of the conventional technique to about +0.0015 mi.

Example 4--Data and computations are as follows

z (ft)	$10^6\gamma$	$\mu_0 = 346.5 \times 10^{-6}$; x = 164.8991 mi
1,497	358	$\Sigma \Delta x = 163.9$ mi; $\Sigma \Delta y = -0.10424$ mi
4,000	454	y = -0.10430 mi; 2r = 329.5896 mi
20,322	1110	Conventional: 2r = 329.5861 mi

In this case the small-term correction amounted to 1.12×10^{-4} mi, and the error of the conventional technique to about -0.0035 mi.

All of the above examples may be considered normal since the initial choice of μ_0 was invariably a good one. Under abnormal propagation conditions, the conventional computation technique gives relatively large errors and it is of interest, therefore, to check the present technique for such a case. The following example is an artificial one. The initial μ_0, from (20), was a poor choice, so several trial values of μ_0 were used to evaluate the various terms.

Example 5--Data and computations are as follows

$x = 191.5032$ mi

z (mi)	0.000	0.125	0.13	1.13
$10^6 \gamma$	283.0	270.5	270.5	470.5

$10^6 \mu_o$	$\Sigma \Delta x$ (mi)	$\Sigma \Delta y$ (mi)	y (mi)
216.2	72.58	-0.01378	-0.00578
250.0	90.98	-0.01290	-0.00953
265.0	113.13	-0.01235	-0.01090
270.0	141.12	-0.01193	-0.01125
270.41	155.62	-0.01173	-0.01126
270.49	183.26	-0.01136	-0.01125

It can be seen that as soon as the error in x, as computed, becomes less than about 30 pct, the corrected y has a very high order of accuracy. In this case, the correction to y for the neglected small terms amounts to only $+ 0.8 \times 10^{-5}$ mi.

Conclusions--It may be concluded that the proposed technique offers adequate accuracy, and adequate control of the accuracy, for all shoran purposes. The numerical operations involved are simple and can be carried out rapidly and accurately. The proposed method consumes no more time than conventional methods, and has the marked advantage that non-random errors in multiple line-crossings may be greatly reduced by its use.

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DAY-SKY BRIGHTNESS MEASURED BY ROCKETBORNE PHOTOELECTRIC PHOTOMETERS

H. A. Miley, E. H. Cullington, and J. F. Bedinger

Abstract--Several experiments have been conducted since 1946 to measure skylight in the upper atmosphere. From the results, it appears that skylight consists of (1) sunlight scattered by the atmosphere and (2) day airglow (light originating in the upper air by other means than Rayleight scattering). The scattered-light values are large at the ground but decrease rapidly (almost proportional to atmospheric density) until at about 30 km the sky is relatively black, the measured values being about two to three percent (depending on direction) of those recorded at the ground level. The scattered light becomes unimportant in comparison with airglow at about 35 to 40 km. Day airglow appears to be nearly constant in the range 40 to 130 km, and is much larger than expected. Photometers employing interference filters gave day-airglow values which are of the order of 10^4 times the corresponding night-airglow values. Further evidence of large light values at high altitudes is given by photographs of clouds made at an altitude of 70 km. The nature and exact locations of these clouds are to be determined. They appear near enough to have been in the cold layer at about 80 km.

Introduction--The night-sky radiations have been the subject of many research papers, but relatively little has been known about the day sky. The large amount of scattered light (daylight) has prevented daytime low-level investigations of light emitted in the upper atmosphere. A few measurements have been made above the Earth's surface by airplane- or balloon-borne equipment. Day-sky brightness was studied to a height of about six kilometers [LUCKIESH, 1919] by means of an airplane-borne photometric method. More recently, there have been several experiments of this nature, but the results of these airplane-borne measurements will not be reviewed here. Some day-sky brightness measurements were made [TEELE, 1936] to about 22 km using recessed photoelectric cells carried by a piloted balloon. Radiation was measured from a very broad spectral region (no filters were used). Several experiments employing unoccupied balloons, for example, STAIR and COBLENTZ [1938], have been directed toward other types of measurement and have been concerned only indirectly with skylight.

The objective of the experiments here reported was to measure skylight at selected wavelengths by means of rocketborne photoelectric photometers. Stated otherwise, what a photometer (as nearly monochromatic as possible) may "see" in the range from ground-level to the top of the rocket's trajectory was to be recorded.

General problems--Rockets impose difficult requirements on such experiments. The equipment should (1) be light in weight and small in volume, (2) provide pressurized enclosures for the higher-voltage sections, (3) possess self-contained power supplies and respond automatically and instantaneously, (4) be adjustable to a wide range of light intensities, (5) be rugged to the extent of passing severe shake and shock tests, (6) maintain constancy of calibration, or have means for calibration during the flight, (7) provide a d-c voltage signal always acceptable to a high-impedance telemetering system and proportional to light intensity, and (8) be adjustable to a limited number of telemetering channels and to the remote controls for switching on and off the various power supplies before the rocket is launched. There is also the need of a means of tracking the rocket, determining its aspect, and avoiding unwanted radiations from the Sun and from other directions. Photoelectric techniques satisfy more of these requirements than any other method.

Early sky-brightness rocket measurements, 1946 and 1947

Initial flight, November 21, 1946--The equipment for this test was relatively simple. Simultaneous readings were obtained from pairs of phototubes located 180° apart on the V-2 rocket's nose cone (see Fig. 1). One pair of RCA-929 (S4 cathode surface) tubes "looked" through Wratten filters (no. 47) which passed a band of "sky" blue light. Wratten filters (no. 61), which passed a band of green light, were used with a second pair of 929 tubes. A pair of 925 phototubes (S1 cathode surface) and an odd 926 tube (S3 cathode surface) were used without filters.

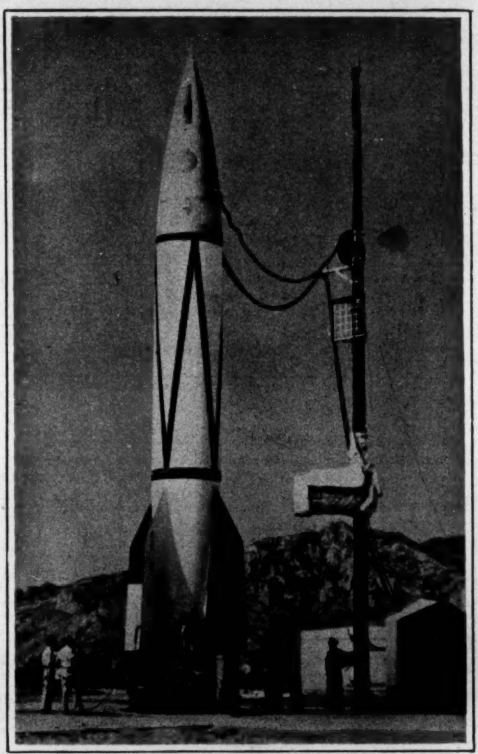

Fig. 1--V-2 rocket, August, 1950, showing positions of two photometer appendages

To avoid direct sunlight, each phototube was recessed into the warhead by means of a brass cylinder (diameter 2.5 cm, length 5 cm); this cylinder was filled with smaller brass cylinders, further reducing the conical space from which light was received to subtend a disk of the sky having a radius of about 12°. A Pyrex glass window, closing the outer end of the larger cylinder, was almost flush with the outside of the rocket. The elevation angle of each photometer direction was 15° when the rocket was on the launching stand. Four of the phototube mounts were attached to the west access door of the nose cone and three of them to the east door. Each phototube was commutated to its respective circuit which consisted of a d-c amplifier, a cathode follower, a voltage divider, and a pair of clipper tubes (Fig. 2). Figures 3 and 4 give curves for four of the photometers, with associated wavelengths of 4430 and 5230 A respectively. At a height of 25 km the sky was found to be relatively dark. The respective intensities of the light passed by the blue and green filters were about 5.7 and 4.6 pct of the amounts received at an altitude of five kilometers for the west-access-door photometers, and about ten and eight per cent for the east-door ones (the firing time was 10h 15m). The measurements obtained from the east-door photometers contain some error due to scattering of sunlight by particles on the window glass. The west door

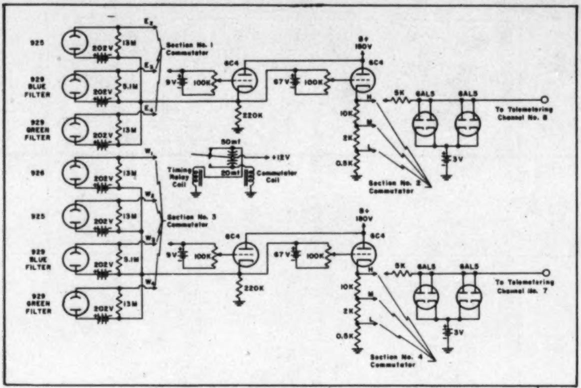
925
929 BLUE FILTER
929 GREEN FILTER
926
925
929 BLUE FILTER
929 GREEN FILTER
202V
13M
5.1M
E2
E3
E4
W1
W2
W3
W4
Section No. 1 Commutator
Section No. 3 Commutator
9V
100K
6C4
220K
67V
B+ 180V
50mf
20mf
+12V
Timing Relay Coil
Commutator Coil
H
M
L
10K
2K
0.5K
5K
6AL5
3V
To Telemetering Channel No. 8
To Telemetering Channel No. 7
Section No. 2 Commutator
Section No. 4 Commutator

Fig. 2--Circuit used in November, 1946

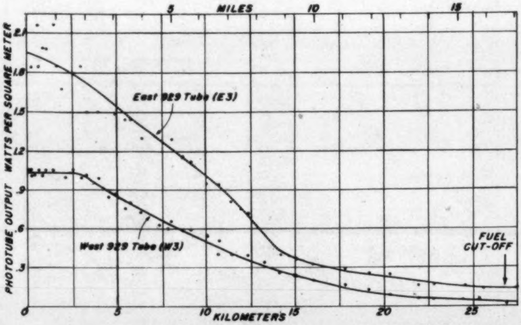

Fig. 3--Phototube responses with blue filters

was in the shadow of the rocket before fuel cut-off since the rocket was gyro-controlled during this period. The ratio of blue light to green light measured from the western direction was about 3.9 at 5 km, 3.9 at 10 km, 3.3 at 15 km, and 3.3 at 20 km. When one compares the west-door values with pressure and density data in the range from about five to 35 km, the results are of an order of magnitude indicating that most of the light resulted from Rayleigh scattering. In order to gain sensitivity needed for upper-air readings, the near-the-ground response suffered because of "clipper" suppression. This source of error was avoided in the 1950 test. Between fuel cut-off (about 27 km) and the top of the trajectory (about 101 km) the rocket rotated about five times. The results showed the need for more sensitive equipment with smaller viewing angle.

Laboratory and field tests--In order to calibrate each phototube, its response to the light passed by its filter was compared with that of a standard thermopile receptor. The latter in turn was calibrated by means of a standard lamp obtained from the National Bureau of Standards. The measurement of filtered light for a given direction is expressed in watts per square meter for 20 A band width from a hemisphere. This represents the 20 A band of energy received by a flat

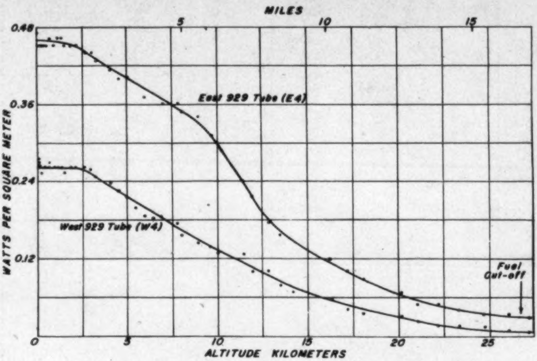

Fig. 4--Phototube responses with green filters

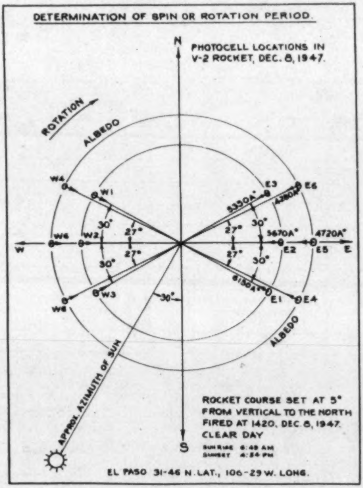
DETERMINATION OF SPIN OR ROTATION PERIOD.
N
PHOTOCELL LOCATIONS IN
V-2 ROCKET, DEC. 8, 1947.
ROTATION
ALBEDO
W4
W1
E3
E6
5350A°
4280A°
30°
27°
W6
W2
W
5670A°
4720A°
E2
E5
E
27°
30°
W8
W3
30°
6150A°
E1
E4
ALBEDO
APPROX. AZIMUTH OF SUN
ROCKET COURSE SET AT 5°
FROM VERTICAL TO THE NORTH
FIRED AT 1420, DEC. 8, 1947.
CLEAR DAY
SUNRISE 6:49 AM
SUNSET 4:54 PM
S
EL PASO 31-46 N. LAT., 106-29 W. LONG.

Fig. 5--Phototube azimuth angle positions, December, 1947

surface of one square meter from a hemisphere of diffuse scattering with intensity equal to the average value of that received by the recessed phototube from the given direction. The associated wavelength is located at the center of the 20 A band. The details of the method of calibration will be discussed in another paper. Ground measurements of skylight made at the launching site near flight time serve as useful calibration references.

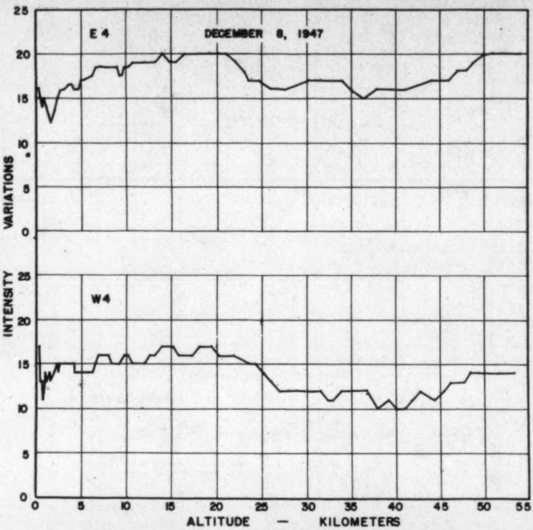

Fig. 6--Albedo measurements (see Fig. 5, E_4, W_4)

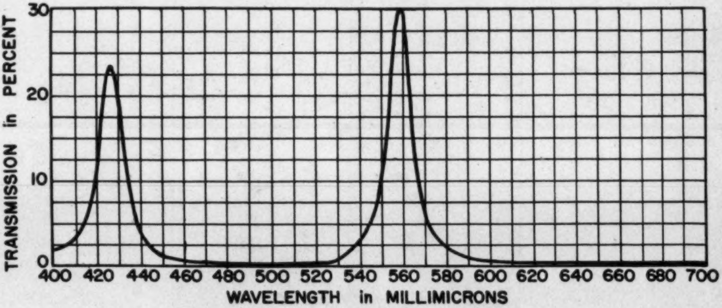

Fig. 7--Transmission curves for interference filters used in August, 1950

Flight of December 8, 1947--Twelve multiplier phototubes (931A) were used for making measurements in the visible light range, six mounted on each of the access doors of the V-2 rocket nose cone (Fig. 5). Two of the phototubes measured the albedo of the Earth. They were mounted 180° apart, with their lines of sight towards the Earth and 15° away from the longitudinal axis of the rocket. Front-surfaced mirrors, mounted at angles of 45° under streamlined hoods, reflected the light to the two phototubes. Figure 6 gives the values obtained.

The remaining five pairs of phototubes measured the light passed by interference filters with peaks at about 4280, 4720, 5350, 5670, and 6150 A. The response curves of the filters were similar to those shown in Figure 7 in spectral width and transmission characteristics. The circuit

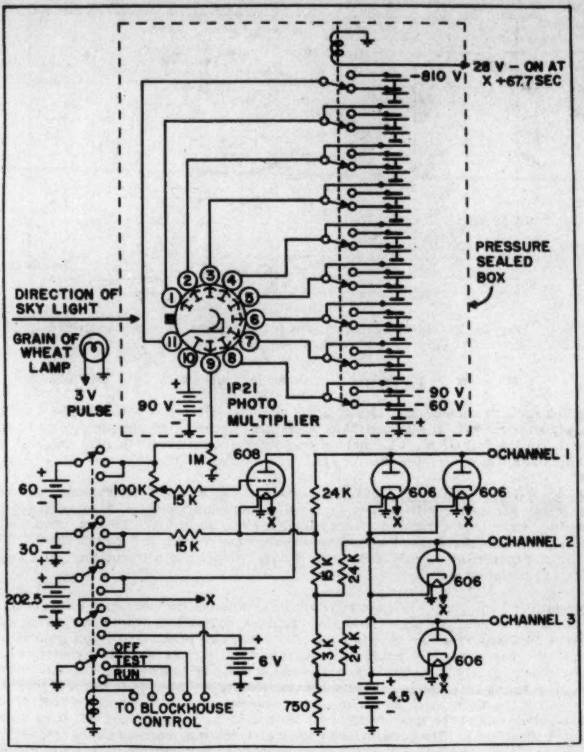
28 V - ON AT
X +67.7 SEC
-810 V
PRESSURE
SEALED
BOX
DIRECTION OF
SKY LIGHT
GRAIN OF
WHEAT
LAMP
3 V
PULSE
1
2
3
4
5
6
7
8
9
10
11
90 V
IP21
PHOTO
MULTIPLIER
- 90 V
- 60 V
1M
608
60
100K
15 K
30
202.5
X
6 V
OFF
TEST
RUN
TO BLOCKHOUSE
CONTROL
24 K
606
CHANNEL 1
CHANNEL 2
CHANNEL 3
10 K
24 K
3 K
750
4.5 V

Fig. 8--Circuit diagram of equipment used in August, 1950

was essentially the same as that shown in Figure 8 except that the output of each phototube was commutated at a cathode-follower voltage divider to obtain four ranges of sensitivity. At launching time, the elevation angle of the ten viewing directions was 15°, and the respective azimuth angles were as shown in Figure 5. The combination of more highly responsive phototubes with interference filters provided photometers comparable in sensitivity to those used in 1946 with no appreciable change in viewing angle.

The equipment worked well until failure (of extraneous origin) occurred soon after fuel cut-off. Figure 9 shows the intensities measured from the five eastward directions. Only relative values are given since the thermopile detector used in 1946 was not sensitive enough for use with interference filters. As to order of magnitude, the measurements made in 1946 were confirmed. The west-east relationships for the 14h 20m firing of 1947 were, in general, similar to the east-west relationships for the 10h 15m firing of 1946 (Fig. 3 and 4). Again, as in 1946, accuracy in the near-the-ground values was exchanged for increased sensitivity needed for higher altitudes.

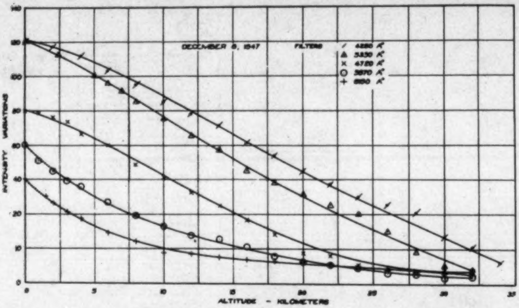

Fig. 9--Intensity-altitude curves for phototubes directed eastward (see Fig. 5)

More recent sky-brightness rocket measurements, 1950 and 1951

The V-2 rocket maintains nearly a constant azimuth orientation before fuel cut-off and usually rolls slowly after cut-off. It was desirable, therefore, to design photometers so as to eliminate a large portion of the roll effect. The main purpose of the experiments in 1950 and 1951 was to measure skylight at altitudes greater than 30 km.

V-2 rocket flight, August 31, 1950--The results of the previous experiments dictated several changes. First, greater sensitivity was provided by using multiplier (1P21) phototubes. This in turn permitted reducing the viewing cone's radial angle to about 5.5°. Finally, photometer appendages were utilized to change the viewing direction and thereby reduce the effects of roll of the rocket. Other experiments in this rocket necessitated dispensing with rotating parts such as the commutators used previously.

Procedure and equipment--Figure 1 shows the location of two photometer appendages on the surface of the nose cone. Through collimator openings, cylindrical beams of light six mm in diameter were admitted, from the direction parallel to the axis of the rocket to right-angled prism-mirrors, where they were reflected through appropriate filters to multiplier phototubes. Figure 10 represents schematically the optical system used for these and subsequent experiments. The appendages provided an irregularly shaped collimator cavity, bounded by the skin of the rocket and the inner wall of the appendage; the prism mirror was mounted at the center of the appendage. The inside and outside of the appendages and a section of the rocket's surface above them (Fig. 1) were painted a flat black. The pressurized photometer box was mounted on the inside of the nose-cone door (a removable section of the rocket's skin). It contained the filters and multiplier phototubes, a single bank of "Minimax" (30-volt) batteries which supplied voltages to the different stages of the two phototubes, and a Ledex solenoid switch which provided an amplification of phototube current at a flight time of 67.7 sec by changing the stage voltages from 60 to 90 volts. The auxiliary circuits of the photometer, shown in Figure 8, were in an unpressurized box. A Price rotary relay switch served well during the preflight controls and tests conducted from the blockhouse. The voltage divider, shown in Figure 8, provided three ranges of sensitivity. Each range was connected to a separate telemetering channel, thus avoiding the use of moving parts. Each channel contained a clipper tube (the highest sensitivity range employed two clipper tubes in parallel) for rejecting signals too large for the system. In

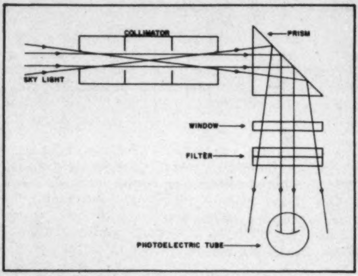

Fig. 10--Diagram of typical collimator

this way, at least one channel's signal was expected to be unclipped at any given time, though the intensities might vary over a wide range. Grain-of-wheat lamps inside the photometer were used to monitor phototube response during the blockhouse tests. Light-tight covers on the collimator openings were automatically removed by means of air resistance just after take-off.

Filters and calibration--The response curves of the interference filters, as obtained with the Hardy spectrophotometer at the Massachusetts Institute of Technology, are shown in Figure 7. The 4260 A filter was chosen to pass the recognized N_2^+ emission band at 4278 A in the night airglow and auroral spectra. The 5590 A filter was selected to pass the oxygen line at 5577 A in night-sky, twilight, and auroral spectra.

The calibration method used will be discussed in another paper. Briefly, sky-radiation values read from a standard optical unit, employing a multiplier phototube as detector, were compared with those read from a unit to be flown. The energy values of the readings from the standard unit of known optical geometry are determined by using standard lamps calibrated in absolute units by the National Bureau of Standards.

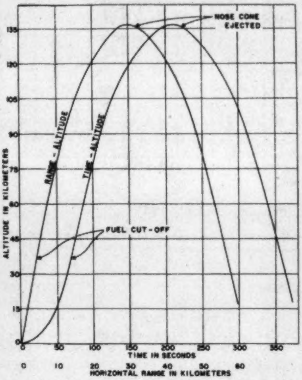

Fig. 11--Trajectory for V-2, August, 1950

In changing telemetered voltages to light intensities, calibration curves were used which took into account the appropriate ratios of input to output for (1) the voltage divider connected simultaneously to three telemetering channels as it was in flight (Fig. 8), (2) the cathode follower, and (3) the phototube when used with a one-megohm load resistor.

The rocket's performance--The range-altitude and time-altitude curves are presented in Figure 11. The rocket's attitude in azimuth and elevation after fuel cut-off (as determined by telescopic and radar tracking systems) are shown in Figures 12 and 13. During the powered portion of the flight, the rocket's aspect was gyro-controlled by its trajectory requirements, and remained fairly constant. After fuel cut-off, it can be seen (Fig. 12 and 13) that the rocket precessed at a slow rate, until at the top of the trajectory the longitudinal axis of the rocket was pointing at about azimuth 190° (referred to north) and elevation about four degrees; in other words, the rocket was flying nearly backwards as it passed through the highest point of its trajectory.

Results, 1950--Since no commutator was used, the photometers yielded continuous records. Figures

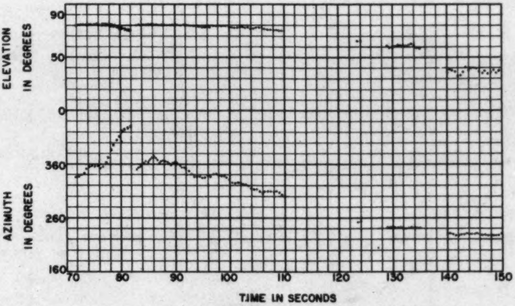

Fig. 12--Aspect data from 70 to 150 seconds, August, 1950
(x indicates solution nears indeterminateness)

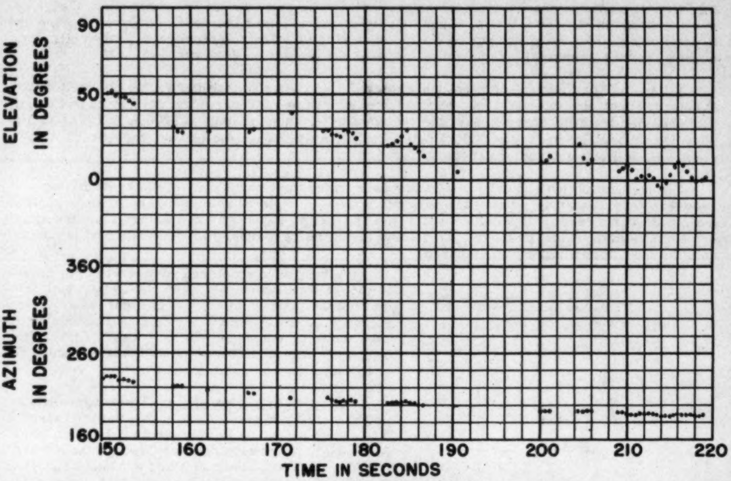

Fig. 13--Aspect data from 150 to 220 seconds, August, 1950

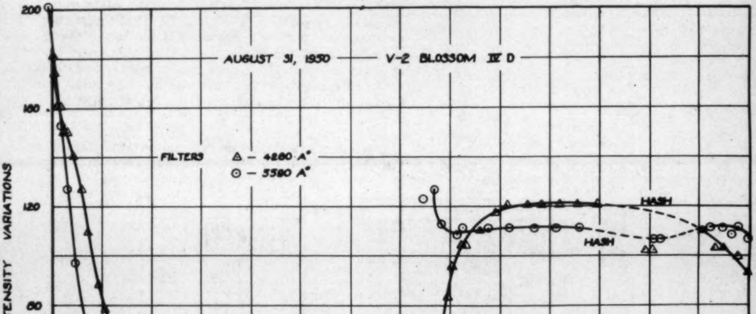

Fig. 14--Altitude-intensity curves from ground level to 70 km (for absolute values see Table 2)

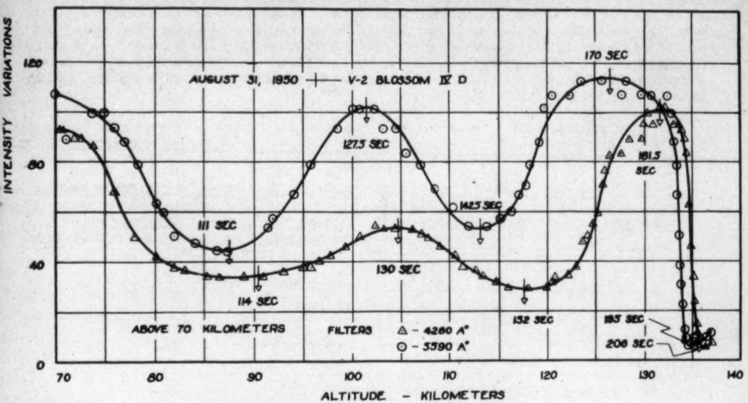

Fig. 15--Altitude-intensity curves from 70 to 136 km
(for absolute values see Table 2)

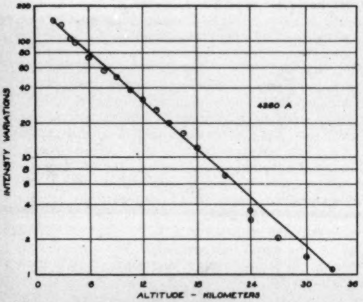

Fig. 16--Log of intensity versus altitude for 4260 A filter

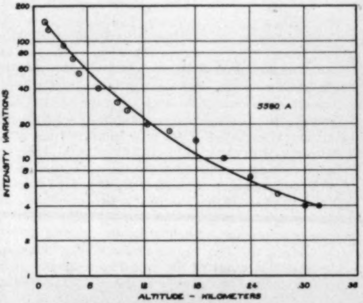

Fig. 17--Log of intensity versus altitude for 5590 A filter

14, 15, 16, and 17 give representative values read from these recordings. Figure 14 shows that light intensity decreases rapidly, and nearly exponentially (see Fig. 16 and 17) from ground level to an altitude of about 35 km. It appears from these results that most of the light measured in this range is due to Rayleigh scattering. The intensities at 30 km were about one to two per cent of those at ground level.

For the remainder of the flight, the values are largely independent of altitude. Both the constancy and large order of magnitude of the readings were astonishing. Obviously, Rayleigh scattering cannot account for these results. The light values began increasing after fuel cut-off at 67 sec (Fig. 14), and the change of stage voltage provided an amplification of about 25; the combination of both effects produced excessively large readings in the range from about 40 to 70 km. As readings so large had not been anticipated, no calibrations were available for this sensitivity range.

The cyclical nature of the data may be connected with the rotation of the rocket. The tracking telescopes gave a roll period of 60 sec in the range from fuel cut-off to 70 km; no roll information was obtained beyond 70 km. A large object was ejected from the rocket at an altitude of about 70 km and this may have altered the rotation period. These cyclical effects include intensity changes due to (1) the revolution of the photometer appendages alternately through the sunny and shaded areas of the rocket, (2) the precession of the rocket (Fig. 12 and 13), and (3) variations in skylight with directions. (When the rocket was fired at 10h 9m 11.8s, the Sun's azimuth was 124° 31′ and its elevation 54° 00′; when the rocket reached the top of the trajectory at 10h 12m 52.8s, the Sun was at azimuth 125° 46′ and elevation 54° 38′).

Taking the minimum values in the neighborhood of 85 and 115 km as representing the amount of light at these altitudes and in the viewing direction of the photometers, the comparisons shown in Table 1 are obtained (see Table 2 also).

Table 1--Comparison of the intensities of light in microwatts per square meter for 20 A band widths received from a hemisphere[a]

Filters	Light intensity at		
	30km	85 km	115 km
A			
4260	10×10^3	6×10^3	5.2×10^3
5590	12×10^3	5.5×10^3	6.6×10^3

[a] The hemisphere of diffuse scattering has an intensity equal to the average value of that received by the recessed phototube from the respective direction. The associated wavelength is located at the center of the 20 A band.

Table 2--The factors for converting relative values of 1950 data to absolute values in microwatts per square meter for 20 A band width received from a hemisphere (see footnote to Table 1)

Filters	60 volts/stage multiply by	90 volts/stage multiply by
A		
4260	4.5×10^3	1.7×10^2
5590	3.0×10^3	1.2×10^2

Although these 1950 results seemed spectacular and very significant, publication of them in a scientific journal has been withheld until the evidence of large, nearly constant light values at high altitudes could be verified with different equipment and for additional wavelengths.

Aerobee rocket flight, July 25, 1951--Equipment was designed to the specifications of an Aerobee rocket (which was launched at 09h 25m) for measuring day airglow in the upper atmosphere. The tip of the rocket's nose cone was jettisoned (this detachable nose cone was supplied by the University of Colorado in connection with an Air Force contract), at about 35 km, admitting light through a series of eight interference filters mounted on a single rotating disk. Two independent columns of light, each about six mm in diameter, were admitted to openings in the disk. These columns were received from the direction of the longitudinal axis of the rocket. In this way independent spectral series of light values were presented to be recorded each half second (the rotation period of the disk). The two recording photometers were operated at different sensitivity ranges and each served as a calibration check on the other. The ninth opening in the rotating disk contained a grain-of-wheat lamp, burning at constant voltage, to provide a calibration service during the flight. The radius of the conical viewing angle was about four degrees. The filters were "peaked" at most of the well-known lines and bands in the visible range, and some were selected for measuring the energy in the spectral airglow "windows."

Results, 1951--Only one telemetering channel was available for recording the data from the rotating disk. This greatly limited the range of sensitivity that could be employed. The phototube outputs for the set of eight filters varied greatly on account of differences in (1) phototube spectral sensitivity, (2) filter transmissions, and (3) the expected spectral distribution of day airglow. An attempt was made through the use of neutral filters to bring all the responses within the sensitivity range.

The readings showed that the intensity of light recorded was somewhat greater than that measured in 1950 and that the filter combinations in the range from 4200 to 5900 A transmitted more light than could be recorded. Readings from three filters were within the acceptable sensitivity range and are given in Figure 18. These results show that the large and constant amount of light measured in 1950 has been verified at other wavelengths. The constant values measured at these three wavelengths are given in Table 3 (see Table 4 also). From the known sensitivity limit of the equipment, the light intensity for the respective regions of the other five filters can be shown to be greater than the values given in the third column of Table 3.

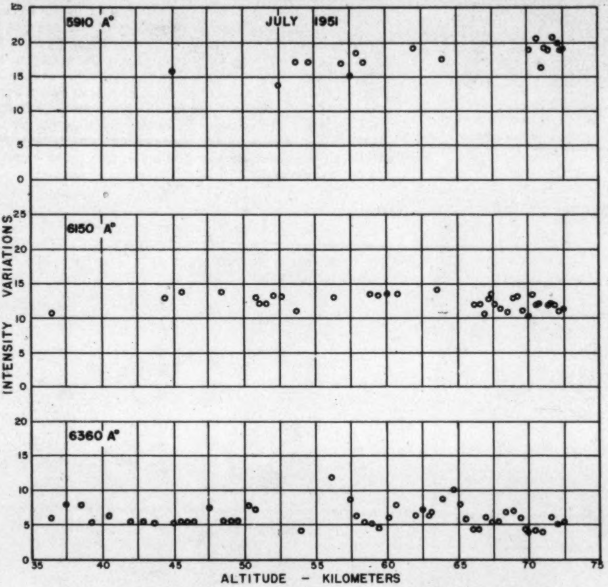

Fig. 18--Relationship of intensity to altitude for three filters flown in July, 1951 (for absolute values see Table 4)

Table 3--Comparison of the intensities of light in microwatts per square meter for 20 A band widths received from a hemisphere (see footnote to Table 1)

Filters A	Average value 30 to 70 km	Values 30 to 70 km are greater than	Ground value at flight time
6360	6.9×10^3	......	2.3×10^5
6150	6.0×10^3	......	2.5×10^5
5910	3.3×10^3	......	1.5×10^5
5590	......	2.0×10^3	8.3×10^5
5390	......	1.1×10^3	2.3×10^5
4895	......	1.9×10^3	6.3×10^5
4615	......	1.4×10^3	5.0×10^5
4290	......	0.9×10^3	3.3×10^5

The magnitude of the light values obtained in 1950 suggested that a sensitive camera be carried in the 1951 flight. Accordingly, a camera was mounted in the rocket so that it was "looking" in the same direction as the photometers. The camera was a modified GSAP, with focal length of 25 mm, relative aperture of f 4.5, shutter time of 1/400 second, frame rate of 6.67 per second, and Eastman Lenographic Pan film; standard development as prescribed by the Eastman Kodak Co. was used. Representative photographs of clouds taken when the rocket was at an altitude of about 70 km are shown in Figure 19. These three photographs were taken from successive

Table 4--The factors for converting relative values of 1951 to absolute values in microwatts per square meter for 20 A band widths received from a hemisphere (see footnote to Table 1)

Filters	90 volts/stage multiply by
A	
6360	9.2×10^2
6150	5.0×10^2
5910	2.2×10^2

frames of 16-mm film and show clearly the rotation of the rocket with a period of the order of a second. It is believed that these clouds are above an altitude of 70 km because of (1) the fact that no evidence of rocket instability has been obtained (aspect data obtained to an altitude of 55 km showed the rocket to be flying very stably), (2) the apparent nearness of the clouds to the camera (lower atmospheric clouds photographed from such an altitude would appear much smaller and more sharply outlined), and (3) the photometer values (Fig. 18) obtained while the rocket was known to be stable (from aspect data) did not change; these photometers did record saturated values after parachute ejection when they were expected to "look" earthward.

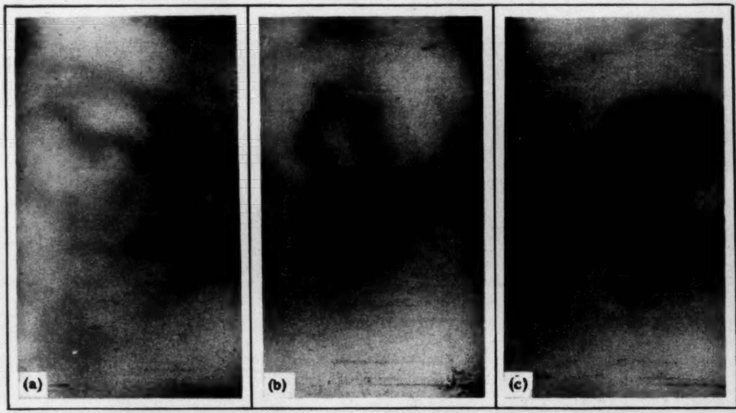

Fig. 19--Photographs of clouds recorded by a rocketborne camera at an altitude of about 70 km (portions shown represent an area 8 × 11 mm on the original negatives)

The nature and exact location of these clouds remain to be determined. From the photographs they appear near enough to be in the cold layer at about 80 km, and may consist of ice crystals. Silvery noctilucent clouds are known to exist near the base of the ionosphere during twilight [VESTINE, 1934]. In northern countries, they have been seen often when illuminated by the oblique rays of the Sun from below the horizon. This is possibly the first time these clouds have been observed in the daytime or photographed at close range. Noticeable changes in the clouds, during the time of nearly half a second for recording the three frames, indicate the effects of the strong winds believed to exist at this altitude.

General discussion

In general the major results may be summarized as shown in Figure 20. Scattered light refers to Rayleigh scattering; emitted light includes all light originating in the upper atmosphere by other means than Rayleigh scattering. Scattered light, I_1, decreases exponentially from the ground until at altitude A_2 (about 35 km) it is negligible. Light of high-altitude origin, labeled emitted light, I_5, remains constant (about two per cent of I_2) to the highest altitude obtained (135 km). For a particular wavelength, intensity I_2 from a radiating hemisphere was recorded as 0.25 watt per square meter for a 20 A wide energy band peaked at 6150 A (Table 3). At 35 km this value was reduced to six milliwatts per square meter, or 2.4 pct of I_2. This value was constant to the peak of the flight (70 km). None of the rockets reached a so-called "emitting layer" and the curve

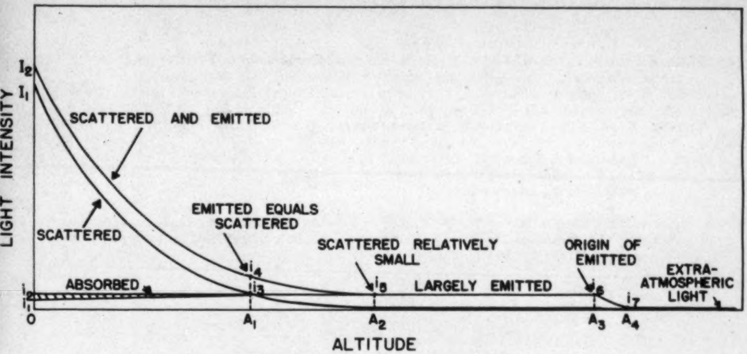

Fig. 20--Proposed diagram of what a monochromatic photometer may "see" while traversing the Earth's atmosphere (not drawn to scale)

from this point on is speculative, being based on knowledge of the upper atmosphere, night-sky light, and existing theories of the origin of such light.

According to different theories, night airglow may originate from one of the following: (1) stored potential energy, particularly from photochemical reactions, (2) recombinations made possible by the dissociations and ionizations produced by the ultraviolet radiations from the Sun, and (3) particles from outside the Earth's atmosphere, possibly from the Sun.

Day airglow is probably in large part emitted light due to an absorption-and-emission process that takes place in atoms and molecules under certain conditions. Thus, at various levels in the atmosphere, the Sun's energy is absorbed by a particular kind of atom or molecule and then radiated in all directions. The emission process which causes day airglow may be of two types. First, a very slow emission (based largely on the recombination of ions) which continues for a long time, even through the night. This is termed "night airglow" and, although very weak, it can be measured from the ground at night during the absence of the scattered light present in the daytime. However, the measurements presented in this paper have shown the day airglow to be of the order of ten thousand times the night airglow. This suggests that a second type of emission is present, namely, a resonance scattering or a fluorescent scattering type, or both. That is, one which takes place only while the atoms or molecules are absorbing at the same time they are emitting. Thus, when the Sun is not shining on the upper atmosphere, the emission of this type ceases; this also applies to any contribution made to airglow by light reflected or scattered by high-altitude clouds. On this basis, the night airglow might be considered to be largely what is left over of the ion-recombination type of day airglow. It is now considered that the certainty of the surprisingly large day airglow is established.

Acknowledgments--The principal contributions of the respective physicists and electronic engineers were as follows: H. A. Miley (physicist) as project scientist was assisted by D. F. McClellan (electronic engineer) with the design, construction, and calibration of the 1946 and 1947 equipment, as field engineer in connection with the 1947 experiments, and with the interpretation of the results of 1946 and 1947; by E. H. Cullington (electronic engineer) with the design and construction of the 1950 and 1951 equipment, as field engineer in connection with the 1946, 1950, and 1951 experiments, and with the interpretation of the results of these three sets of experiments; by J. F. Bedinger (physicist) with the calibration of the 1950 equipment, the interpretation of the 1950 results, and with all phases of the 1951 experiments; and by E. H. Murphy (physicist) with the reduction and interpretation of the 1950 data, and with the calibration of the equipment of 1950 and 1951. Thanks are due M. D. O'Day, the Air Force Cambridge Research Center, the Holloman and White Sands Bases, and the Wentworth Institute for splendid cooperation.

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THE EFFECT OF THE OCEANIC DUCT ON MICROWAVE PROPAGATION

L. J. Anderson and E. E. Gossard

Abstract--A body of experimental radio and meteorological data taken over Cardigan Bay, on the British west coast, is examined to ascertain how radar propagation is affected by the microwave duct lying next to the sea surface. The boundary-layer meteorological profiles are analyzed in terms of a semi-empirical relation due to E. L. Deacon, and propagation is predicted according to a method of S. A. Schelkunoff. At three-cm wave-lengths, it is found that the agreement between observation and theory becomes steadily better as wind speed increases, until at speeds above 15 mi/hr (7 m/s) the consistency is truly striking. At lower wind speeds there is a definite tendency to follow the theoretical pattern, but a great deal of scatter is noted. Possible explanations for this scatter are offered.

More scatter is observed at nine cm than at three cm, and the transition to trapping conditions is less definite. The nine-cm waves appear to "feel" the effects of the duct some time before trapping occurs.

An interpretation is offered of the fact noted by McPetrie and Starnecki that, in general, high signals are associated with large positive air-sea temperature differences, while low signals are accompanied by large negative differences. Also, Jones' observation that, under unstable conditions, high winds are accompanied by high signals is nicely explained.

Theory--One may define a "potential refractive index" in the atmosphere as

$$\phi = (79/\theta)\,(P_o + 4800\, e_p/\theta)$$

where θ = potential temperature, e_p = potential vapor pressure, and P_o = 1000 mb. Furthermore, it can be shown [ANDERSON and GOSSARD, 1952] that the vertical profile of ϕ may be adequately represented by assuming its functional expression to be the same as that of the meteorological parameters, θ and e_p, by which it is determined. We shall further assume that the meteorological parameters have a height distribution in accordance with a semi-empirical law advanced by DEACON [1949]. From detailed wind and temperature measurements, Deacon found that such parameters as wind, temperature, and moisture could be represented by a height distribution of the form

$$df/dh = ch^{-\beta}$$

where f may represent wind, $\theta_h - \theta_o$, $(e_p)_h - (e_p)_o$, etc., and where β is a profile index which is less than unity under stable atmospheric conditions and greater than unity for instability. It is to be noted that when $\beta = 1$ the profile reduces to the conventional logarithmic form. Furthermore, β seems to be nearly equal for all of these meteorological parameters.

With these assumptions, we have

$$\Delta\phi = \phi_1 - \phi_o = c\int_{z_o}^{h_1} h^{-\beta}\, dh \qquad (1)$$

where

h = height

β = profile index, a function of stability (see Fig. 1), $\beta > 1.0$ unstable, $\beta = 1.0$ neutral (logarithmic), and $\beta < 1.0$ stable

z_o = a small length characteristic of the roughness of the surface and is tabulated for a variety of surfaces; in this paper it has been assumed equal to 0.02 ft (0.6 cm) for winds ≥ 15 mi/hr and 5×10^{-5} ft (0.0015 cm) for winds < 15 mi/hr

ϕ_o = potential refractive index of sea surface

c = a constant of proportionality

In Deacon's experiments, he found the profile index β to be a function of stability as defined by Richardson's number

$$J = (g/\theta)\,\frac{d\theta/dh}{(du/dh)^2}$$

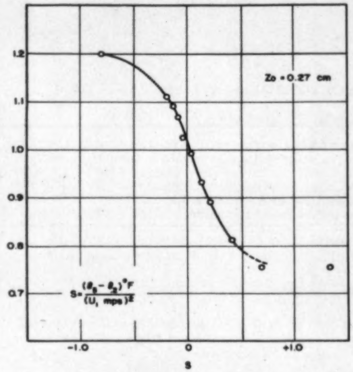


Fig. 1--The variation of β with stability [DEACON, 1949]

where u = wind speed. He further showed that for a given set of conditions, such as known instrument heights and surface roughness, J was uniquely related to a parameter S, defined by the relation

$$S = (\theta_2 - \theta_1)/(u_3)^2$$

where subscripts refer to arbitrary heights. He then obtained an empirical curve relating S and β which may be translated to other sets of conditions if one assumes the β profile to be correct throughout the boundary layer. Deacon's original curve is shown in Figure 1 for his experimental conditions, in which temperatures were measured at heights of 5 and 0.2 m and wind at one meter.

In order to assess the effect of surface ducts over the sea upon the propagation of radar energy, we are concerned mainly with determining whether or not the duct is sufficiently well developed to trap energy of a given wavelength, since only under trapping conditions will radar coverage be appreciably extended. The approximate method of SCHELKUNOFF [1944] is well suited to the establishment of such a criterion.

Schelkunoff replaces the actual refractive-index profile within the duct by a two-layer model having an equivalent effect on the vertical distribution of field strength. Each layer is assumed to have constant refractive index, with the lower layer extending from the sea surface to a height H. If H is a real quantity for a given wavelength, then energy of that wavelength is trapped.

The relation connecting H, λ, and the actual profile shape M(h) is given by Schelkunoff as

$$H\int_0^H M(h)\,dh - H^2 M(h) = (9 \times 10^6/128)\,\lambda^2 \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Substituting for M(h) its equivalent, $\phi(h) + 0.04h$ in (2), we obtain to a good approximation

$$H^3\left\{H^{-\beta}[(\beta - 1)/(2 - \beta)]\Delta\phi/(h_1^{1-\beta} - Z_o^{1-\beta}) - 0.04/2\right\} = (9 \times 10^6/128)\,\lambda^2 \ldots\ldots\ldots (3)$$

where H is the height of the discontinuity in the fictitious distribution of M; h, λ, and Z_o are in feet; and h_1 is height at which ϕ_1 is measured, for example, bridge height on a ship.

To obtain the critical value of H for which trapping just occurs, we differentiate the left-hand side of (3) and set the derivative equal to zero. Substituting this critical H back into (3) and writing the resulting expression in a form such that the right-hand side is a function of wavelength only, we define a parameter which we shall call X, by the equation

$$X = \left[\frac{(3 - \beta)(\beta - 1)}{0.06\,(2 - \beta)}\;\frac{\Delta\phi}{h_1^{1-\beta} - Z_o^{1-\beta}}\right]^{3/\beta} \beta/(3 - \beta)$$

Trapping should occur when X reaches the critical value X_c given by

$$X_c \geq 3770\,\lambda^2$$

where λ is the wavelength in centimeters.

Observational verification--The only suitable observations available to check the above theoretical deductions were contained in an excellent body of data taken on a 56-mile (90-km) path over Cardigan Bay, off the west coast of England and loaned to the authors by J. S. McPetrie. These data have been analyzed in terms of X, the parameter previously derived.

The lowest transmitter and receiver heights at Cardigan Bay were 97 ft (30 m), at which height the meteorological data were also taken. Unfortunately, this puts transmitter and receiver so high above the optimum level on the height-gain curve assumed by Schelkunoff that signals due to ducting should be well below the values which would be observed at the optimum level. Thus we would assume that other factors which could affect propagation would tend to obscure the effects of the surface duct and cause considerable scatter about a prediction based solely on the existence of this duct.

The points selected for comparison with theory were based on the meteorological observations taken at Aberdaron and Fishguard, the two ends of the link. The points were so chosen that steady-state conditions could be fairly reliably assumed; that is, the meteorological parameters were not changing rapidly. This practice tended to emphasize conditions of maximum and minimum meteorological values. Observations taken during fog or rain were rejected, as were those for which the temperature, humidity, or wind was unrecorded (unless reliable interpolation was possible). For three of the 11 months analyzed, some airplane soundings were available. When these soundings gave definite indication of abnormal profiles aloft, the surface observations were not used. Finally, in a few cases when there was a very large discrepancy between observations at the two ends of the link, the points were neglected. In general, averages of observed values at the two ends of the link were used, weighted somewhat toward the end having the wind off the water.

Results--The results of the analysis are presented in Figures 2-7. The major features are listed below.

(1) As wind speed increases, the scatter of the observations becomes less until, as shown in Figure 2, at wind velocities greater than 15 mi/hr nearly perfect agreement with theory is noted on X band.

It is seen from Figure 3 that somewhat more scatter is noted on S band. No sharp break appears to take place in the range of X observed, but rather a general rise in field strength is observed as X increases toward the critical value.

(2) At lower wind velocities, the scatter becomes quite pronounced as seen in Figures 4 and 5. A median line through the data has been drawn such that near a given X, half the points lie above the line and half lie below. From this line it is seen that the tendency noted in Figures 2 and 3 is still present. It is perhaps significant that a critical wind speed occurring at about Beaufort 4 (15 mi/hr) was assumed in this analysis. This concept is open to some question as indicated by experiments done by Neumann and Roll in Germany, by Francis and Sheppard in England, and by the U. S. Navy Electronics Laboratory. Lacking conclusive evidence, however, it was decided to adopt the conventional approach and assume the sea surface to be transformed from a hydrodynamically smooth to a rough surface at a critical wind velocity. And, indeed, it was noticed in analyzing the data that under unstable conditions trapping often seemed to occur as

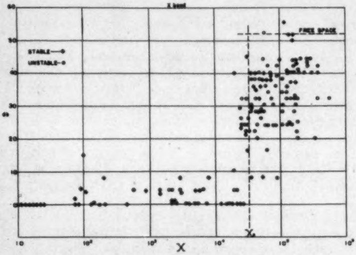


Fig. 2--Relation of field strength in db above one microvolt/meter to X; X band, wind ≥15 mi/hr

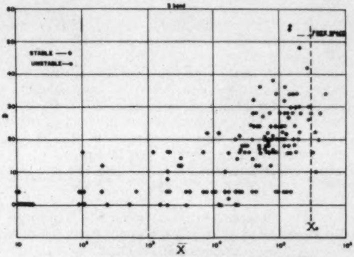


Fig. 3--Relation of field strength to X; S band, wind ≥15 mi/hr

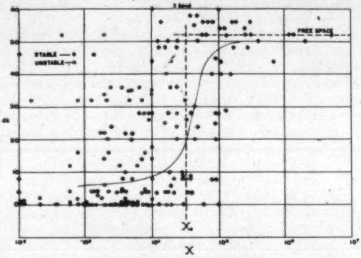


Fig. 4--Relation of field strength to **X**; X band, wind <15 mi/hr

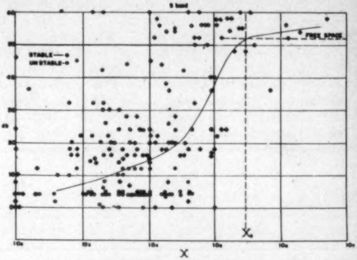
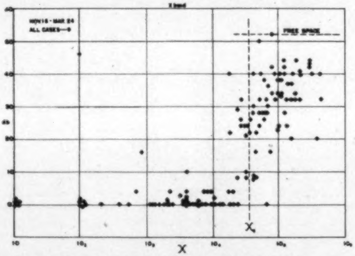


Fig. 5--Relation of field strength to **X**; S band, wind <15 mi/hr



Fig, 6--Relation of field strength to **X**; X band, Nov. 16-Mar. 24, all winds

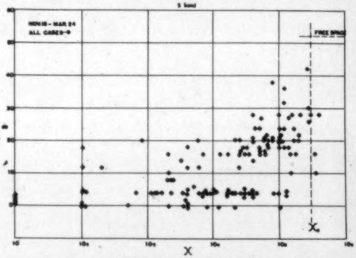


Fig. 7--Relation of field strength to **X**; S band, Nov. 16-Mar. 24, all winds

the wind speed approached Beaufort 4 although **X** would not have exceeded X_c unless a critical wind velocity had been assumed. Actually, a variety of factors probably contribute to the observed scatter at low wind speeds. Listed in the inverse order of their probable importance, they are:

(a) At low wind speeds, small errors in meteorological parameters cause large errors in the profile index β, particularly under stable conditions, because of the shape of the curve showing the relationship of S to β.

(b) At low wind speeds, the mixed layer near the surface is relatively thin, and features other than surface phenomena may be relatively more important. Furthermore, we find most cases of quite low wind speed occurring in summer when inversions aloft are rather prevalent. For example, PETTERSSEN, SHEPPARD, PRIESTLEY, and JOHANNESSEN [1947] in analyzing soundings in March-August, 1943, found 54 days (about 1/3 of the time) when subsidence inversions were present. On 17 pct of these days the subsidence inversion was below 3200 ft (one km). Furthermore, they analyzed only those inversions definitely due to subsidence. This explanation is further supported by the fact that during the winter months when the water is generally warmer than the air, resulting in a thick mixed layer, and when at the same time periods of anticyclonic conditions which breed subsidence inversions are few [LAMB, 1950], the agreement between observation and theory is excellent even though the wind is less than 15 mi/hr about one-third of the time (Fig. 6-7).

(c) It is noticeable that when winds are low and air-water temperature differences are large, the signal ranges somewhat erratically from very high values to very low ones. This seems to suggest that inhomogeneities along the path are important when wind speeds are low. Since buoyancy forces become important when wind speeds are low and the air is warmer than the water, one would expect a tendency for katabatic drifting and thus considerable differences in the thickness of the boundary layer should occur along the path. On the other hand, when wind speeds are low but with the air colder than the water, one would expect a tendency for convection cells to form along the path, with corresponding variations in duct height and refractive-index distribution.

(d) However, the most important contribution to the scatter of points at very low wind speeds probably arises from the purely artificial effects of radiation on the meteorological observations taken over lard at the two ends of the link. As stated earlier, the meteorological observations were taken about 100 ft above the sea surface at land stations. The observed values at the two ends were then averaged and assumed to represent corresponding values at the same height over the sea. With a brisk sea breeze blowing, this assumption would appear to be quite adequate. However, when wind speeds are low, heating over land during the day and cooling at night may well cause the land observations to differ appreciably from those over the link. Furthermore, this effect is coupled with that of paragraph (4a) and also emphasized by the previously mentioned selection of "steady-state" conditions, which usually resulted in the selection of points either from the warm midday or the cold early morning. It was noted while analyzing the data that the greatest disparity between observation and theory occurred on those days when there was a large diurnal swing in the meteorological elements. It was also true that large discrepancies in meteorological measurements at the two ends of the link in general were associated with low wind speeds. In general, such conditions were characteristic of the summer months.

(3) MacPETRIE and STARNECKI [1948] have shown that for those cases when air-water temperature differences exceeded 5° F (2.8° C), stable conditions usually led to higher signals than unstable ones. These observations are nicely explained under the present hypothesis, as seen in the scatter diagrams for low wind speeds, that is, when stability effects are relatively important. It is noted in Figures 4 and 5 that very few cases of instability exceeded the critical value of X required for ducting, while the latter was often exceeded in the stable case with a consequent prediction of higher signals. This is a result of the behavior of the profile index β as a function of stability.

(4) JONES [1949], on the other hand, has pointed out that when the air is colder than the water, high signals are generally associated with high wind speeds. This observation also is accounted for by the present model. For example, if Figures 2 and 4 are compared, it is striking that a much larger proportion of the unstable points exceed the critical X for high wind speeds than for low ones. This also is primarily a result of the manner in which β varies with stability as defined by Richardson's number, which, as pointed out, includes the square of the wind speed gradient in the denominator.

Conclusions--It appears that if transmitter and receiver were lowered to near the maximum of the height-gain curve, and if meteorological measurements were actually taken over the sea at fairly low levels, impressively good agreement with the model proposed in this paper would be observed. Despite the adverse factors inherent in the present data, the agreement is very encouraging at higher wind speeds. Furthermore, some features found difficult to explain previously are accounted for in this model. These include the correlation between high signals and large positive air-sea temperature differences and the tendency under unstable conditions for high winds to be associated with high signals.

The frequency dependence predicted by the present theoretical expression is left somewhat in doubt, but it is likely that this is a result of the large scatter on S band and the method of analyzing the data, since it is well known from other experiments [KATZIN, BAUCHMAN, and BINNIAN, 1946] that stronger oceanic ducts are needed to trap ten-cm waves than to trap three-cm waves. This is in qualitative agreement with the model herein proposed.

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EVALUATION OF PROBABLE MAXIMUM PRECIPITATION

J. L. H. Paulhus and C. S. Gilman

Abstract--Probable maximum precipitation is defined and a distinction is drawn between it and probable maximum storm. The maximizing procedure used in the derivation of probable maximum precipitation for specific areas consists chiefly of moisture adjustment and, when justifiable, transposition of observed storms. Moisture adjustment of a storm involves the estimation of the increased precipitation that would be expected if maximum atmospheric moisture were available. Transposition involves the adjustment of the precipitation of storms observed outside the problem area for differences in meteorological and topographic effects between their original sites and the problem area. It is in effect an extrapolation of the record of storm experiences for the area.

Introduction--The concept of using meteorology to derive limiting precipitation values for hydrologic design originated in the middle 1930's. From meteorological knowledge, attempts were made to fix physical upper limits to the rainfall that could occur over certain basins during specified time intervals. Such is the conceptual definition of probable maximum precipitation, also known as maximum possible precipitation. The values derived as probable maximum precipitation under this definition are naturally subject to change as our knowledge of the physics of atmospheric processes increases.

Speaking of probable maximum precipitation, SHERMAN [1944] wrote: "(a) It should be used in the design of all structures which, in the event of failure, would involve large loss of life and property damage; (b) the values for runoff thus derived call for no additional factor of safety, since the factor has been cared for by the concatenation of possible events; and (c) it furnishes far more reliable limits than any data derived by statistical analysis. The latter, based on a long-time record, does furnish a possible check on the engineer's computations and may aid him in deciding whether a particular structure warrants the elimination of certain remote hazards."

In addition to the conceptual definition of probable maximum precipitation, one may consider an operational definition as consisting of the steps followed by hydrometeorologists in arriving at the answers supplied to engineers for design purposes. Whatever the philosophical objections to the concept, the operational definition leads to an answer that has been examined thoroughly by competent meteorologists and engineers and has been judged as meeting the requirements of a design criterion. The result of application of the operational definition over the entire country is to approach uniformity in safety and cost.

Probable maximum storm--Although the term probable maximum, or maximum possible, storm appears infrequently in hydrometeorological literature since 1945, it was used liberally in earlier papers and reports. It was then understood to be a fictitious or synthetic storm that could produce probable maximum precipitation over a given area for all durations, and the terms precipitation and storm were used interchangeably. A distinction between the two is now generally recognized. The probable maximum precipitation for a specific area is usually determined by several types of storms. For example, a thunderstorm is very likely to provide probable maximum precipitation over an area under 100 sq mi for durations of 24 hours or less, but the controlling values for longer durations will almost invariably be obtained from general storms. It is, therefore, usually illogical to assume that the probable maximum precipitation for all durations could be realized from one storm. There are exceptions, of course. For regions such as southeastern Alaska, which hardly ever experiences thunderstorms and where major rainfalls are practically all associated with occluded systems moving inland from the Gulf of Alaska, it is reasonable to expect that the probable maximum precipitation for all durations up to five days over the largest areas covered by individual general-type storms could be obtained from one storm, which could then be properly labeled the probable maximum storm.

Unfortunately, the terms probable maximum precipitation and probable maximum storm are used by some hydrometeorologists to indicate the precipitation that would produce the probable maximum flood, which in many areas would be a combination snowmelt and rain flood, with the former being by far the major contribution. Furthermore, since the conversion of precipitation into stream flow involves hydrologic considerations such as infiltration rates and other basin characteristics, the derivation of the probable maximum flood is a problem for the engineer. The hydrometeorologist, however, is charged with the responsibility of providing the engineer with prospective design storms in the form of one or more observed storms adjusted for their maximum potential production of rainfall in the project basin, together with advice on possible variations in the distribution of rainfall with respect to time and location. This practice is gaining acceptance, especially for large basins. Other conditions being equal, the resulting design flood will have a smaller safety factor than one based on probable maximum precipitation, but it is entirely adequate for most structures.

Derivation of probable maximum precipitation--The maximizing procedures applied to actual storms in determining probable maximum precipitation include moisture adjustment and, when justifiable, transposition. Admittedly, there are other factors besides moisture that are active in the precipitation-producing process. These factors determine the efficiency of the storm, or its effectiveness for converting atmospheric moisture into precipitation. FLETCHER [1948] suggested that precipitation could be considered as a function of moisture and one over-all "convergence factor" that might serve as an index of storm efficiency. There is a wide variation in the efficiency of different storms so that it is possible to obtain various precipitation amounts from equal initial moisture charges. The hydrometeorologist, however, does not adjust storms to maximum efficiency for three reasons: (1) So little is known of storm structures and the factors controlling efficiency that it is practically impossible to make a reliable estimate of the efficiency of a particular storm, let alone to estimate the probable maximum efficiency. (2) The major observed storms used for deriving probable maximum precipitation undoubtedly produced heavy precipitation because of their high efficiencies rather than because of unusually large moisture charges, so that a long record of storms will very likely contain some of near probable maximum efficiency. (3) It is generally suspected that the maximum efficiency of a storm is realized when the moisture charge is not at a maximum. Consequently, adjustment to maximum moisture for estimating probable maximum potential is probably an overadjustment that compensates for the absence of adjustment for probable maximum efficiency.

Transposition is the maximizing procedure that has been most universally accepted by engineers. The basic assumption is that the particular location of a storm depends largely on meteorological factors that could just as easily have occurred over a different location. Limits to free transposition are presented by orography or by transition from a region generally subject to one type of storm to a region subject to other types. A storm would not be transposed across the Appalachian barrier from the Atlantic Seaboard to the Ohio Valley. Neither would a hurricane from the Gulf littoral in Louisiana be transposed to the Mississippi Valley near the Arkansas-Missouri border, where all observed hurricanes have undergone pronounced modifications.

The first step in deriving the probable maximum precipitation for a project area is the selection of major storms that either have occurred in the area or that could have occurred in the area under slightly different meteorological conditions. Maximum depth-area-duration data (see example in Table 1) for several hundred major United States storms are available so that it is usually a relatively simple matter to select critical storms for a particular area. The procedure for obtaining these data has been described by LINSLEY and Others [1949].

Table 1--Maximum depth-area-duration data for the Thrall, Texas, storm of September 8-10, 1921 (after Corps of Engineers)

Area	Duration of rainfall in hours						
	6	12	18	24	30	36	48
sq mi	in	in	in	in	in	in	in
Maximum station	23.4	31.8	36.4	38.2	39.2	39.7	39.7
10	22.4	29.8	35.0	36.5	37.2	37.6	37.6
100	19.6	26.2	30.7	31.9	32.6	32.9	32.9
200	17.9	24.3	28.7	29.7	30,4	30.7	30.8
500	15.4	21.4	25.6	26.6	27.3	27.6	27.7
1,000	13.4	18.8	22.9	24.0	24.6	24.9	25.1
2,000	11.2	15.7	19.5	20.6	21.2	21.5	21.6
5,000	8.1	11.1	14.1	15.0	15.9	16.2	16.3
10,000	5.6	7.7	9.7	10.7	11.8	12.1	12.2
12,500	4.7	6.7	8.4	9.4	10.3	10.7	10.9

The moisture adjustment used in maximizing storms consists of multiplying the observed rainfall values by the ratio of the maximum observed moisture in the basin for the time of year the storm occurred to the moisture in the storm. Since most of the major storms that have been analyzed occurred before there was an adequate network of upper-air soundings, it is necessary to use the surface dewpoint as an index of the moisture in the storm and of the maximum moisture in the basin. Under the assumption of a saturated pseudoadiabatic atmosphere, the amount of moisture is a unique function of the ground elevation and surface dewpoint. The moisture adjustment can then be determined from the dewpoint observed at the time of the storm and the maximum dewpoint ever observed in the project area. These dewpoints are subject to two qualifications: (1) In accordance with frontal theory, the storm dewpoint is measured in the warm air rather than at the point of rainfall, which is quite frequently in the cold air. (2) Obviously, the moisture must be that which persists for a period of at least several hours. Tests have indicated that the lowest dewpoint in the 12-hr period corresponding most nearly to the 12-hr period of greatest rainfall is fairly representative of average moisture in the storm center. This dewpoint is called the representative 12-hr persisting dewpoint. The maximum 12-hr persisting dewpoint to which the storm values are adjusted is the highest value below which the dewpoint did not drop during any 12-hr period of record. All dewpoints are generally reduced pseudoadiabatically to the 1000-mb level to make the dewpoints for stations at different elevations comparable and to permit the use of tables and charts of moisture in atmospheric columns with base at 1000 mb. Maps of maximum dewpoints and tables of moisture content, expressed in terms of precipitable water, have been published by the U. S. **WEATHER BUREAU** [1948, 1951].

Three methods of moisture adjustment have been described by **FLETCHER** [1951], but only two are in general use, both yielding approximately equivalent results. In one case the adjustment factor is simply the ratio of the precipitable water, corresponding to the maximum 12-hr persisting dewpoint in a layer between the highest inflow barrier to the storm precipitation center and the 200-mb level, to the precipitable water in the same layer but corresponding to the storm's representative 12-hr persisting dewpoint. In the other case, the factor is based on the so-called thunderstorm model, essentially the same as described by **SHOWALTER** and **SOLOT** [1942], the dimensions of which vary with surface dewpoint (Fig. 1). Table 2 shows that there is little difference between the moisture adjustment factors obtained by the two methods. The slight differences between the two are due solely to the fact that the top of the thunderstorm model varies from 300 mb at a 50° 1000-mb dewpoint to 100 mb at 78° while the top of the air column in the simple precipitable water adjustment is constant at 200 mb.

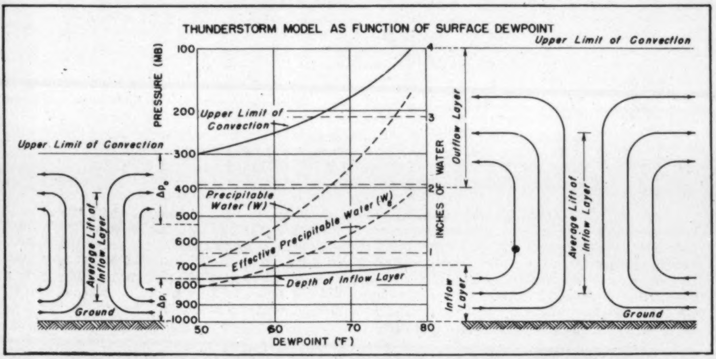

THUNDERSTORM MODEL AS FUNCTION OF SURFACE DEWPOINT
Upper Limit of Convection
Upper Limit of Convection
PRESSURE (MB)
100
200
300
400
500
600
700
800
900
1000
Upper Limit of Convection
Precipitable Water (W)
Effective Precipitable Water (W_e)
Depth of Inflow Layer
INCHES OF WATER
4
3
2
1
DEWPOINT (°F)
50
60
70
80
Δp_o
Δp_i
Average Lift of Inflow Layer
Ground
Outflow Layer
Average Lift of Inflow Layer
Inflow Layer
Ground

Fig. 1--Thunderstorm model, which is divided into three equal pressure layers, has top varying linearly with vapor pressure of surface dewpoint; original maximizing moisture adjustments were based on ratios of effective precipitable water (W_e), which is defined as $W_e = W_i - (\Delta p_i/\Delta p_o) W_o$, but ratios of precipitable water (W) are almost the same, so latter are now generally used

Table 2--Moisture adjustment factors (after U. S. Weather Bureau)

1000-mb dewpoint	Precipitable water at 78° F	
	Thunderstorm model	1000- to 200-mb column
°F	pct	pct
50	24.9	25.0
52	27.6	27.6
54	30.5	30.5
56	33.8	33.8
58	37.3	37.4
60	41.2	41.3
62	45.6	45.6
64	50.3	50.4
66	55.6	55.7
68	61.4	61.5
70	67.7	67.7
72	74.5	74.6
74	82.4	82.4
76	90.7	90.8
78	100.0	100.0

It should be noted that increases to maximum moisture are not made without regard to seasonal limitations. In other words, the moisture in a January storm would never be increased to that indicated by the highest dewpoint, which usually occurs in late summer. In practice, the moisture adjustments are made to the highest dewpoint for the same time of year as the storm occurrence or to the highest dewpoint within 15 days (Fig. 2).

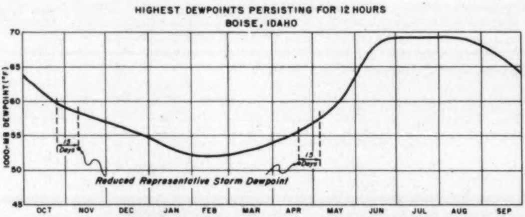


Fig. 2--Moisture adjustments are generally based on the highest maximum dewpoints within 15 days of the date of storm occurrence; thus, in the case shown in this figure, the storm of November 10 would be adjusted to the October 26 dewpoint of 60°, while the storm of April 20 would be adjusted to the May 5 dewpoint of 58°

An example of maximization involving transposition is shown in Figure 3. The problem in this example is to maximize an October 1 storm occurring on the Kansas-Oklahoma border to its maximum rainfall-producing potential over a project basin in South Dakota, assuming that this storm could occur there under slightly different meteorological conditions. The height of the inflow barrier to the original site is 1000 ft, and to the project basin, 1500 ft, msl. Because it is reasonable to expect that this storm could have occurred at least 15 days earlier, when dewpoints are higher, with very little change in structure or dynamic efficiency, the maximization is based on mid-September dewpoints (Fig. 3).

Assuming now that the 1000-mb representative 12-hr persisting dewpoint for the storm was 72° F and was recorded at a point 200 mi south of the storm precipitation center, we find that the maximum 12-hr dewpoint for that location is indicated by the isolines of Figure 3 to be 77° F. To adjust the storm for maximum moisture charge at its original site, its precipitation, that is, its maximum depth-area-duration data, would be multiplied by the ratio of the precipitable water (W) above 1000 ft when the 1000-mb dewpoint temperature is 77° F to that for the same layer when the

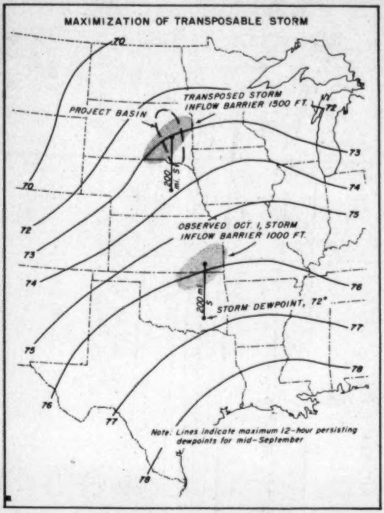

MAXIMIZATION OF TRANSPOSABLE STORM
70
70
PROJECT BASIN
TRANSPOSED STORM INFLOW BARRIER 1500 FT.
72
73
74
75
76
77
78
72
73
74
75
76
77
78
200 mi. S
OBSERVED OCT. 1, STORM INFLOW BARRIER 1000 FT.
200 mi. S
STORM DEWPOINT, 72°
Note: Lines indicate maximum 12-hour persisting dewpoints for mid-September

Fig. 3--Typical storm-transposition problem; rotation of storm pattern to produce heavier rainfall over project basin is not shown here but is usually limited to 20° from original orientation

1000-mb dewpoint temperature is 72° F, or $(W_{77}/W_{72})_{1000}$. This adjustment obviously always results in an increase.

A second adjustment is made to compensate for the fact that, as indicated by the maximum dewpoint lines of Figure 3, there is obviously less moisture available at the transposed site than at the original. Using the same relative displacement of the storm's representative dewpoint, that is, 200 mi south of the precipitation center in its transposed location, we find that the maximum mid-September dewpoint is 74° F. Assuming for the moment that there is no difference in elevation between the two sites, that is, both at 1000 ft, we apply a second adjustment for the difference in moisture, or $(W_{74}/W_{77})_{1000}$. In this particular example, this second adjustment is a reduction, but it could be an increase if, for example, the transposition were in the opposite direction.

A third adjustment compensates for the difference in elevation between the original and transposed sites. This adjustment is the ratio of the precipitable water above the inflow barrier to the transposed site for the maximum dewpoint to that above the inflow barrier at the original site for the same dewpoint, or, in this example, $(W_{74})_{1500} \div (W_{74})_{1000}$.

The three adjustments easily combine into one simple operation so that for our example

$$P_{max} = [(W_{77}/W_{72})_{1000} \times (W_{74}/W_{77})_{1000} \times (W_{74})_{1500}/(W_{74})_{1000}]\,P = [(W_{74})_{1500}/(W_{72})_{1000}]\,P \quad . . .(1)$$

Since W_{74} for a column from 1500 ft to 200 mb is 2.40 in. and W_{72} for a column from 1000 ft to 200 mb is 2.27 in., the over-all adjustment factor is 1.06. The thunderstorm model yields a factor of 1.07.

After all major storms that have occurred in the project basin and that could be transposed to the basin have been maximized, they are used to construct depth-area-duration curves of the probable maximum precipitation (see dashed curves of Fig. 4). Usually only a few of the relatively numerous maximized storms will provide controlling points on these curves.

Maps of probable maximum precipitation for areas of 10, 200, and 500 sq mi and for durations of 6, 12, 24, 36, and 48 hr have been constructed by the U. S. WEATHER BUREAU - CORPS OF ENGINEERS [1947] for the eastern half of the United States. Figure 5 gives values of probable maximum precipitation for 200 sq mi and 24 hr and shows their relation to observed major storms. The table of Figure 5 and the diagram below it show the distribution of the ratios of observed to probable maximum rainfall for 300 major storms. One storm yielded 97 pct of the probable maximum rainfall for its location, 44 yielded 50 pct or more, and 170 yielded 30 pct or more.

Selection of probable maximum storm pattern--It is not recommended that the probable maximum precipitation values be used as applying to one storm. It is even possible that none of the values can be recommended as applying to a particular basin. Direct use of the values may be unrealistic for the most critical storm for the following reasons: (1) Over small basins within the project area, the storm producing critical amounts is not necessarily the same type of storm producing critical amounts over a large basin. Similarly, different types of storms may control for different durations over the same basin. (2) The basin may be oriented in a direction that is impossible for the orientation of the controlling isohyetal patterns. (3) Topography may determine the location of the major isohyetal centers.

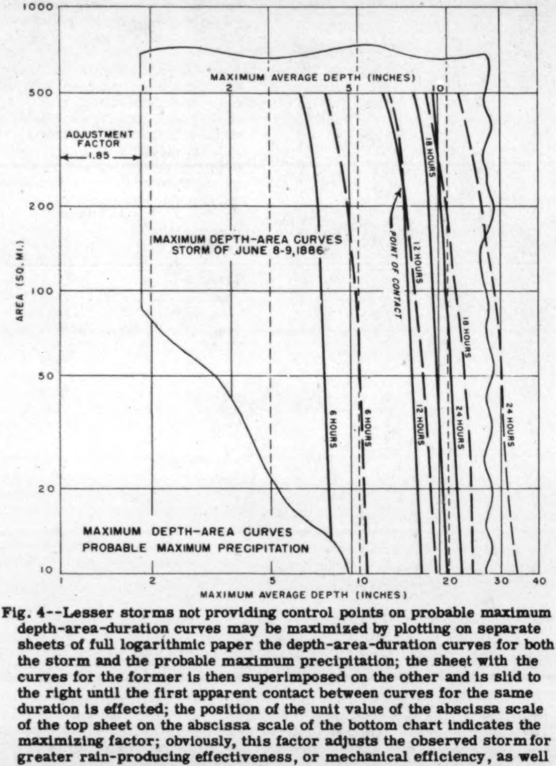
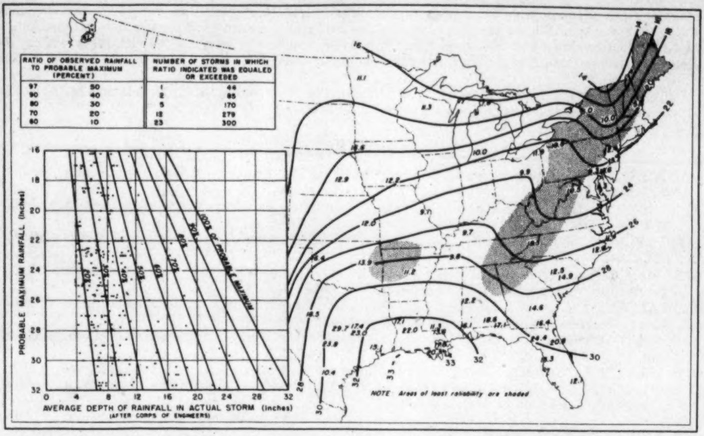


Fig. 4--Lesser storms not providing control points on probable maximum depth-area-duration curves may be maximized by plotting on separate sheets of full logarithmic paper the depth-area-duration curves for both the storm and the probable maximum precipitation; the sheet with the curves for the former is then superimposed on the other and is slid to the right until the first apparent contact between curves for the same duration is effected; the position of the unit value of the abscissa scale of the top sheet on the abscissa scale of the bottom chart indicates the maximizing factor; obviously, this factor adjusts the observed storm for greater rain-producing effectiveness, or mechanical efficiency, as well as for maximum moisture charge

For such reasons, the hydrometeorologist makes recommendations regarding the storm isohyetal patterns that may be applied to a basin for design purposes. These are given in one of two forms: (1) One or more transposed storms may provide a suitable pattern or patterns. Such a choice applies especially when both the basin and the storm site are topographically similar. A limitation may be placed on the rotation or displacement of the isohyetal pattern. If, as often happens, the storms selected provide control points on the probable maximum depth-area-duration curves, no further adjustment is required. (2) If the topography of the project basin exerts a marked influence on its precipitation, a basin storm is usually selected as a pattern. If the storm does not provide points on the probable maximum depth-area-duration curves, it is maximized as in Figure 4. The probable maximum depth-area-duration curves (dashed curved of Fig. 4) are plotted on full logarithmic paper. On another sheet of the same type of paper, and with the same depth and area scales, the maximum depth-area-duration curves (solid curves of Fig. 4) of the storm to be maximized are drawn. The latter sheet is then superimposed on the first and is slid to the right, with the area scales constantly matched, until some point on any of the solid curves lies over a dashed curve of the corresponding duration. The position of the vertical unity line of


PROBABLE MAXIMUM RAINFALL (Inches)
16
18
20
22
24
26
28
30
32
0
4
8
12
16
20
24
28
32
AVERAGE DEPTH OF RAINFALL IN ACTUAL STORM (inches)
(AFTER CORPS OF ENGINEERS)
10%
20%
30%
40%
50%
60%
70%
80%
90%
100% OF PROBABLE MAXIMUM
NOTE: Areas of least reliability are shaded

RATIO OF OBSERVED RAINFALL TO PROBABLE MAXIMUM (PERCENT)		NUMBER OF STORMS IN WHICH RATIO INDICATED WAS EQUALED OR EXCEEDED	
97	50	1	44
90	40	2	85
80	30	5	170
70	20	12	279
60	10	23	300

Fig. 5--Relation of probable maximum precipitation to major observed rainfalls; isolines show values of probable maximum precipitation for 200 sq mi and 24 hr; plotted values are corresponding values actually observed; table and chart on left of figure indicate frequency distribution of storms with respect to ratio of observed to probable maximum precipitation

the top sheet on the horizontal scale of the bottom sheet gives the adjustment factor. Thus, in Figure 4, the 12-hr curves provide the apparent point of contact before any of the other curves, yielding a maximizing factor of 1.85. The same procedure, incidentally, can be used to adjust transposed storms not providing control points on the probable maximum depth-area-duration curves.

The advantages of the adjustment procedure just described become apparent when an ideal situation for its application is considered. For an example, let us consider the determination of the probable maximum storm for a 500-sq mi basin located in the Appalachians. Isohyetal patterns of basin storms show pronounced topographic influences. Also, the records of storms in the region suggest that the basin could experience storms more intense than any that have ever been observed within it.

In accordance with the procedure described in this paper, depth-area-duration data for areas up to 500 sq mi for all transposable major storms in the region would be increased for maximum moisture charge. Next, the adjusted data would be used to construct the enveloping depth-area-duration curves of probable maximum precipitation. The depth-area-duration curves for the basin storm determined to have the most critical areal and chronological distribution are then fitted to the probable maximum precipitation curves, as in Figure 4, to obtain the adjustment factor required to convert the former into the depth-area-duration curves of the probable maximum storm.

Obviously, the procedure yielding the adjustment factor, in effect, increases the record of basin storms. Furthermore, it permits the use of realistic depth-area-duration relationships from critically distributed storm precipitation for deriving the design flood.

Rearrangement of chronological distribution--The flood-producing effectiveness of the storms selected for the design flood may be further increased by the redistribution of the 6-hr precipitation increments in such a way as to increase the runoff. No hydrometeorologist has ever advocated indiscriminate regrouping of the increments solely to give the highest possible runoff, but several periods have been interchanged when his judgment indicated such an interchange was meteorologically possible.

It is obvious that maximization by always adjusting storm amounts upward and selecting the most critical chronological sequences can eventually lead to stream-flow values so high that they would be ridiculous. Since transposition and moisture adjustment produce pronounced maximization for most basins, it is considered that they yield results that are high enough for practical design purposes without further maximization except in unusual cases.

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Washington 25, D. C.

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HORIZONTAL DEFORMATION IN ATMOSPHERIC MOTION

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Abstract--Horizontal fluid deformation is a basic linear property of motion appearing in two forms: stretching and shearing deformation. The resultant deformation, rate and direction, is found by rotating the coordinates through an angle dependent upon the relative values of the two primitive types of deformation in the initial coordinates. Several methods for measuring horizontal deformation in the wind field are introduced and discussed. These employ arbitrary Cartesian coordinates, the latitude-longitude grid of the Earth, the local north-south kinematic directions, and the area outlined between three observation points. The field distribution of deformation for an actual wind field is represented by two methods: (1) by scalar patterns of direction and of rate of deformation, and (2) by a vector method at selected points. The geostrophic deformation is obtained graphically from the geometry of the pressure pattern. The field distribution of deformation is illustrated for several hypothetical pressure patterns simulating common conditions.

Introduction--The change with time in the patterns of physical variables in the atmosphere is a fundamental problem of dynamic meteorology and weather forecasting. The increase and decrease of thermal gradients demands particular attention because of their close relation to changes in the structure of pressure and wind fields throughout the atmosphere and the attendant adjustments through vertical motions. This variation in thermal gradient has been approached under the name frontogenesis (and its opposite, frontolysis). As shown by PETTERSSEN [1935], the rate of frontogenesis, or the rate at which physical surfaces are brought together, is dependent upon the convergence and deformation in the flow in addition to certain non-conservative influences on the temperature.

To remove some of the restriction the word frontogenesis might suggest, we shall prefer to call this general process accumulation of physical surfaces when referring to space or accumulation of isopleths of that quantity when viewing patterns in a plane. It is a convenient way of describing geometrically several important processes changing the structure of the atmosphere, and deformation in the air motion is effective in a variable degree in each of these. Because an adequate knowledge of fluid deformation is basic to an understanding of all these daily occurrences, it is the purpose of this article to describe the property more fully and to show how its horizontal component can be evaluated both mechanically and visually from a given wind pattern. There is no intention of minimizing other factors in accumulation, nor of suggesting that those other factors are adequately known at present.

Linear properties of the field of motion--If u is the wind component along the x-direction and v the wind component along the y-direction in a horizontal coordinate plane, the linear properties of motion at any point in the wind field are [see, for example, STEWART, 1945]

translation	u, v
divergence	$\partial u/\partial x + \partial v/\partial y = 2\,b$
vorticity	$\partial v/\partial x - \partial u/\partial y = 2\,c$
stretching deformation	$\partial u/\partial x - \partial v/\partial y = 2\,a$
shearing deformation	$\partial v/\partial x + \partial u/\partial y = 2\,a'$

Stretching deformation implies change of shape by different rates of stretching along the coordinate axes (Fig. 1). If this deformation is positive, there is stretching along the x-axis and shrinking along the y-axis. The opposite holds for negative deformation. If the motion at P describes pure deformation of this type, the element conserves its area and orientation, and P is the neutral point in a hyperbolic wind field (Fig. 2a). In the more general case with deformation and translation, the center of the element moves with the translation velocity at P, but the element is otherwise affected in the same way.

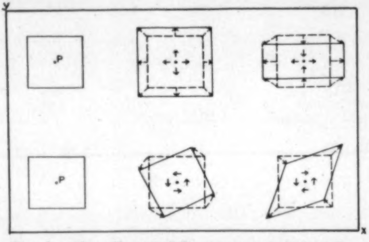


Fig. 1--The effects of divergence and stretching deformation (upper row) and vorticity and shearing deformation (lower row) on an initial square element of fluid

Shearing deformation is related to the vorticity in a manner similar to the apparent relation of stretching deformation to divergence. Stretching deformation is the difference between the two Cartesian components of stretching, while divergence is their sum. Shearing deformation is the difference between the two components of shear, while vorticity is their sum. Shearing deformation is the rotation of one coordinate axis through the particle minus the rotation of the other coordinate axis. If the motion is pure shearing deformation, there is positive shear along one coordinate axis and negative shear of equal magnitude along the other. The net result is an axis of stretching 45° from the coordinate axes and an axis of shrinking normal to the axis of stretching (Fig. 2b); the fluid element again is affected only in its shape.

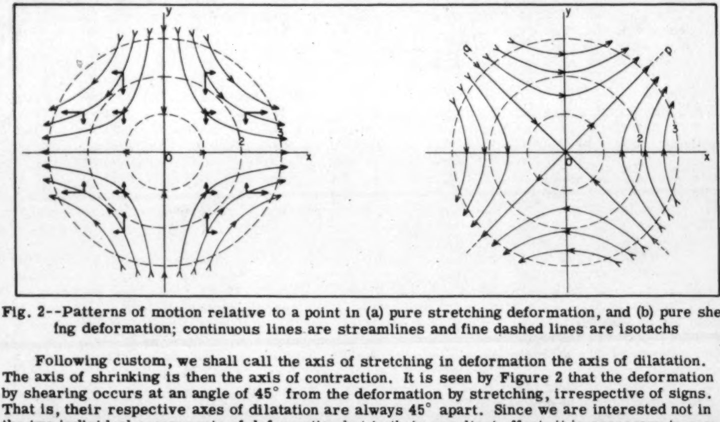


Fig. 2--Patterns of motion relative to a point in (a) pure stretching deformation, and (b) pure shearing deformation; continuous lines are streamlines and fine dashed lines are isotachs

Following custom, we shall call the axis of stretching in deformation the axis of dilatation. The axis of shrinking is then the axis of contraction. It is seen by Figure 2 that the deformation by shearing occurs at an angle of 45° from the deformation by stretching, irrespective of signs. That is, their respective axes of dilatation are always 45° apart. Since we are interested not in the two individual components of deformation but in their resultant effect, it is necessary to combine the two. This one problem is the immediate source of difficulty in understanding deformation and in attempting to apply it in daily weather analysis to the same extent as divergence and vorticity.

Resultant deformation--Neither type of deformation gives individually the desired total rate and sense of deformation in the field of motion, unless the other is zero. To derive any value from the concept, the two types must be combined to give the resultant direction of dilatation (elongation) and also the net rate of deformation. This can be done by rotating the coordinate axes through such an angle that in the new system one type of deformation vanishes at the point in question. This operation will have to be done at each point for which the deformation is determined.

The u and v components of velocity in the initial x,y coordinates are related to the velocity components u_1 and v_1 in the coordinate system x_1,y_1 rotated counter-clockwise through the arbitrary angle θ by

$$\left.\begin{aligned} u &= u_1 \cos\theta - v_1 \sin\theta \\ v &= u_1 \sin\theta + v_1 \cos\theta \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (1)$$

One also can show that horizontal derivatives in the two coordinate systems are related by the operators

$$\partial/\partial x = (\cos\theta)\,\partial/\partial x_1 - (\sin\theta)\,\partial/\partial y_1$$

$$\partial/\partial y = (\sin\theta)\,\partial/\partial x_1 + (\cos\theta)\,\partial/\partial y_1$$

Therefore,

$$\left.\begin{aligned}
\partial u/\partial x &= [(\partial u_1/\partial x_1)\cos\theta - (\partial v_1/\partial x_1)\sin\theta]\cos\theta - [(\partial u_1/\partial y_1)\cos\theta - (\partial v_1/\partial y_1)\sin\theta]\sin\theta\\
\partial v/\partial y &= [(\partial u_1/\partial x_1)\sin\theta + (\partial v_1/\partial x_1)\cos\theta]\sin\theta + [(\partial u_1/\partial y_1)\sin\theta + (\partial v_1/\partial y_1)\cos\theta]\cos\theta\\
\partial v/\partial x &= [(\partial u_1/\partial x1)\sin\theta + (\partial v_1/\partial x_1)\cos\theta]\cos\theta - [(\partial u_1/\partial y_1)\sin\theta + (\partial v_1/\partial y_1)\cos\theta]\sin\theta\\
\partial u/\partial y &= [(\partial u_1/\partial x_1)\cos\theta - (\partial v_1/\partial x_1)\sin\theta]\sin\theta + [(\partial u_1/\partial y_1)\cos\theta - (\partial v_1/\partial y_1)\sin\theta]\cos\theta
\end{aligned}\right\}\ (2)$$

Subtracting $\partial v/\partial y$ from $\partial u/\partial x$ in (2)

$$\partial u/\partial x - \partial v/\partial y = [(\partial u_1/\partial x_1) - (\partial v_1/\partial y_1)]\cos 2\theta - [(\partial v_1/\partial x_1) + (\partial u_1/\partial y_1)]\sin 2\theta \ldots\ldots (3)$$

and adding $\partial v/\partial x$ and $\partial u/\partial y$

$$\partial v/\partial x + \partial u/\partial y = [(\partial v_1/\partial x_1) + (\partial u_1/\partial y_1)]\cos 2\theta + [(\partial u_1/\partial x_1) - (\partial v_1/\partial y_1)]\sin 2\theta \ldots\ldots (4)$$

From these it is apparent that generally

$$\partial u/\partial x - \partial v/\partial y \neq \partial u_1/\partial x_1 - \partial v_1/\partial y_1 \qquad \partial v/\partial x + \partial u/\partial y \neq \partial v_1/\partial x_1 + \partial u_1/\partial y_1$$

In other words, the two types of deformation are dependent upon the particular orientation of coordinates. Rotation of the coordinates alters the magnitude and also possibly the sign of each type of deformation. For this reason it is possible to eliminate one of them. It can be shown from (2) that divergence and vorticity are unaffected by rotation of coordinates.

If we choose to rotate the coordinates about the point in question so that $\partial v_1/\partial x_1 + \partial u_1/\partial y_1 = 0$ at that point, then from (3) and (4)

$$\partial u/\partial x - \partial v/\partial y = [(\partial u_1/\partial x_1) - \partial v_1/\partial y_1]\cos 2\theta \ldots\ldots\ldots\ldots\ldots (5)$$

and

$$\partial v/\partial x + \partial u/\partial y = [(\partial u_1/\partial x_1) - \partial v_1/\partial y_1]\sin 2\theta \ldots\ldots\ldots\ldots\ldots (6)$$

Dividing the second by the first gives

$$\tan 2\theta = (\partial v/\partial x + \partial u/\partial y)/(\partial u/\partial x - \partial v/\partial y) \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The desired angle of rotation for eliminating the shearing deformation is then

$$\theta = (1/2)\tan^{-1}(\partial v/\partial x + \partial u/\partial y)/\partial u/\partial x - \partial v/\partial y) \ldots\ldots\ldots\ldots\ldots (8)$$

As shown by this equation, the angle of required rotation is obtained from the ratio of the shearing to the stretching deformation found in the initial coordinates. If both types of deformation are of the same sign, the coordinates are rotated counter-clockwise through the angle θ to eliminate the shearing deformation; if they are of opposite sign the coordinates are rotated clockwise through this angle.

From (5) and (6) the resultant deformation is

$$\partial u_1/\partial x_1 - \partial v_1/\partial y_1 = (\partial u/\partial x - \partial v/\partial y)\sec 2\theta = (\partial v/\partial x + \partial u/\partial y)\csc 2\theta \ldots\ldots\ldots (9)$$

Given the angle of rotation found from (8) and either rate of deformation in the original coordinates, one is then able to determine the resultant rate of deformation from (9). If $\partial u_1/\partial x_1 - \partial v_1/\partial y_1$ turns out positive, then the x_1-axis is the axis of dilatation and the y_1 -axis, the axis of contraction. If $\partial u_1/\partial x_1 - \partial v_1/\partial y_1$ is negative, the reverse is true.

A more simple formula for the resultant rate of deformation can now be given. Using the trigonometric identity $\sec^2 2\theta = \tan^2 2\theta + 1$, and substituting for $\tan 2\theta$ from (7) into (9), it follows that

$$|\partial u_1/\partial x_1 - \partial v_1/\partial y_1| = \sqrt{(\partial u/\partial x - \partial v/\partial y)^2 + (\partial v/\partial x + \partial u/\partial y)^2} \quad \text{. . . . . (10)}$$

The procedure to be taken in determining the resultant deformation about any point in the field of motion can be summarized as follows: (1) measure the stretching and shearing deformations in the original coordinates; (2) from (7) or (8) find the value of the angle θ; (3) locate the x_1-axis making the angle θ with the original x-axis; (4) determine the sign and rate of deformation from (9); (5) if the resultant deformation is positive the x_1-axis is the axis of dilatation, but if it is negative the axis of dilatation is found perpendicular to the x_1-axis; and (6) the absolute value of deformation and the direction of dilatation are assigned to the point in question. This information gives a complete description of the deformation at that point.

This entire operation is clarified by use of a few examples. Suppose from the first step

$$\partial u/\partial x - \partial v/\partial y = 5 \text{ and } \partial v/\partial x + \partial u/\partial y = 3$$

in units 10^{-5} sec^{-1}. Then from (7), $\tan 2\theta = 3/5$, $2\theta = 31°$ and $\theta = 15.5°$. This case is shown in Figure 3. The axes must be rotated in a positive sense. As $\sec 2\theta = 7/6$ and $\partial u/\partial x - \partial v/\partial y = 5$, the resultant deformation has magnitude $+ 35/6 \times 10^{-5}$ sec^{-1}, and x_1 is the axis of dilatation.

Now if the stretching deformation is -3 and the shearing deformation +5, then $\tan 2\theta = -3/5$, $\theta = -15.5°$, and the axes are to be rotated clockwise by the same amount as in the first example. The function $\sec 2\theta$ is again 7/6; therefore, the resultant deformation is once more $+ 35/6 \times 10^{-5}$ sec^{-1}, and x_1 is the dilatation axis in this example also. For stretching deformation +3 and shearing deformation -5, the axes are rotated clockwise 15.5°, but now y_1 is the axis of dilatation.

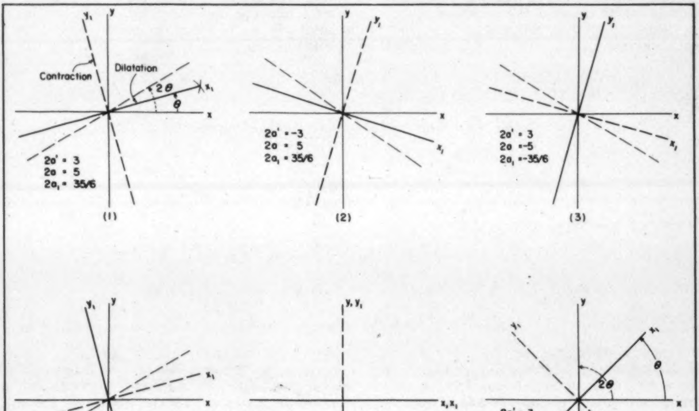


Fig. 3--Resultant direction of deformation for given values of stretching deformation 2a and shearing deformation 2a'

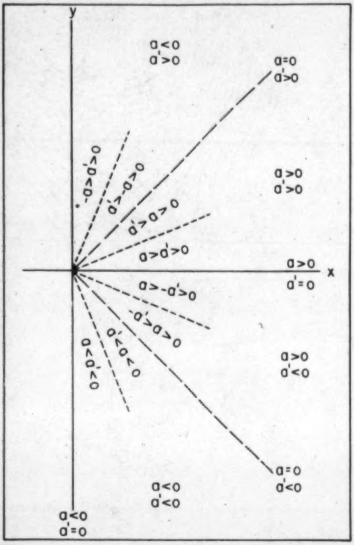


Fig. 4--The direction of dilatation for the given relative values of stretching and shearing deformation

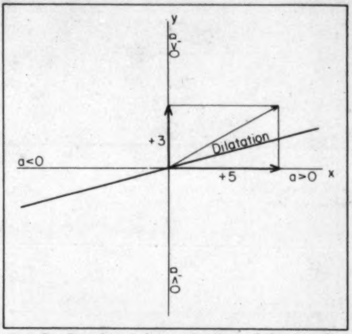


Fig. 5--Graphical determination of the resultant rate of deformation and axis of dilatation given the values of stretching and shearing deformation

Figure 4 serves as a guide for locating the axis of dilatation from given relative values for the stretching and shearing deformation in the original x,y coordinates. A more exact method for graphically determining the resultant rate and direction of deformation from given rates of stretching and shearing deformation is shown by Figure 5. The rates of stretching and shearing deformation are plotted to scale in vector form along the x-axis and y-axis respectively. The length of the resultant vector gives the resultant rate of deformation; see (10). The axis of dilatation is the bisector of the angle between this vector resultant and the positive x-axis.

Measurement of deformation by finite differences in the Earth's coordinate grid--The stretching deformation can be determined from field distributions of west wind (u) and south wind (v) by the formula

$$\partial u/\partial x - \partial v/\partial y \approx \delta u/\delta x - \delta v/\delta y - (v/r) \tan \phi \quad \ldots\ldots\ldots\ldots (11)$$

and the shearing deformation by

$$\partial v/\partial x + \partial u/\partial y \approx \delta v/\delta x + \delta u/\delta y + (u/r) \tan \phi \quad \ldots\ldots\ldots\ldots (12)$$

where r is the radius of the Earth, ϕ is the latitude, and x and y are along the local latitude and longitude, respectively. The correction terms accounting for convergence of meridians are negligible in most instances except near the pole. In the subsequent discussion they are omitted altogether.

As an example we begin with observed winds over the eastern United States given in Figure 6a; the arrow follows the wind direction, and the figure near the point of the arrow gives the wind speed in knots. In Fig. 6b is shown the analysis of this wind field by streamlines and isotachs (isopleths of wind speed). From the patterns of west-wind and south-wind components (not shown), the derivatives $\partial u/\partial x$, $\partial u/\partial y$, $\partial v/\partial x$, and $\partial v/\partial y$ were evaluated at each unit intersection of latitude and longitude (using length unit 120 nautical miles), and then the rates of stretching deformation (Fig. 6c) and shearing deformation (Fig. 6d) were determined at each point with respect to the latitude-longitude coordinate grid. Next, by applying (7), (8), and (9), the resultant rate and direction of deformation were determined at each grid point. These results are shown in Fig. 6c, where isogons of dilatation are drawn for intervals of 15° and intensity of shading is proportional to the rate of deforma-

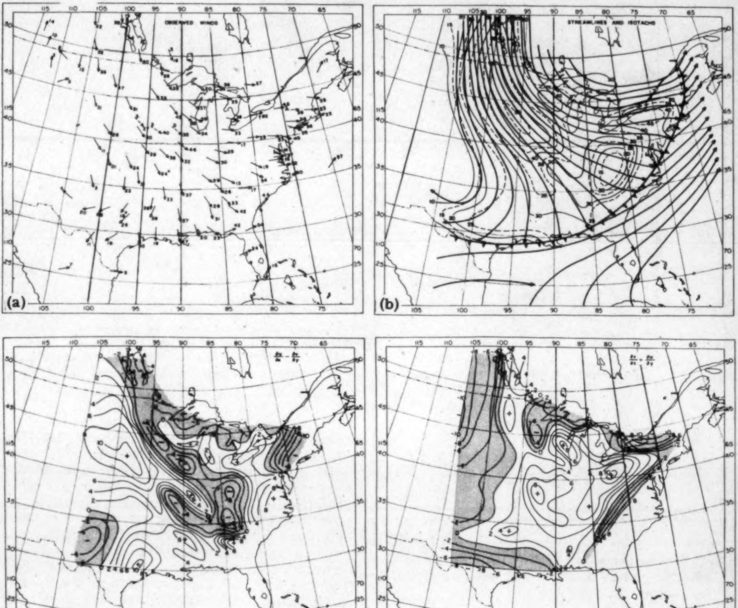

OBSERVED WINDS
STREAMLINES AND ISOTACHS
(a)
(b)
(c)
(d)
(e)
(f)
NW-SE
S-N

Fig. 6--Wind field 4000 ft at 15h 00m G.C.T., March 1, 1950; (a) actual winds; (b) streamlines and isotachs; (c) the stretching deformation; (d) the shearing deformation with respect to the latitude-longitude grid, in units knots per degree of latitude (multiply by 0.46 to get units 10^{-5} sec^{-1}); (e) resultant deformation; (f) vector representation of (e) tion (light stippling, 2 to 4×10^{-5} sec^{-1}; coarse stippling, $> 4 \times 10^{-5}$ sec^{-1}). Figure 6f gives a more legible but discontinuous representation of these results. The axis of dilatation is indicated by a shaft at selected points over the map, and the length of each shaft is drawn proportional to the local rate of deformation (scale indicated). The asterisks are points of no deformation; they are the singular points in Figure 6e. These are difficult to detect in the elementary wind analysis (Fig. 6b).

Measurement of deformation from kinematic directions--In meteorological analysis the local n-s system of directions is often more convenient to apply than the Cartesian system. If s is taken along the streamline and n ninety degrees to the right of the streamline, and if c is the wind speed and α the wind direction in radians, then

$$\partial u/\partial x - \partial v/\partial y = c\partial\alpha/\partial n - \partial c/\partial s \qquad (13)$$

$$\partial v/\partial x + \partial u/\partial y = \partial c/\partial n + c\,\partial\alpha/\partial s = \partial c/\partial n - cK_s \qquad (14)$$

K_s is the curvature of the streamline at the point in question. Definitions of the other components in these equations are indicated in the left side of Table 1. The two types of deformation can be measured from streamline and isotach patterns by means similar to those described in the preceding section, only now the directions n and s are given locally by the wind. The angle of rotation θ (measured from the streamline direction s) necessary to eliminate the shearing deformation follows by substitution into (7).

Table 1--The direction of dilatation relative to the streamline (or wind) direction due to the individual components of deformation

Condition	Direction
Longitudinal stretching ($\partial c/\partial s > 0$)	Along the streamlines
Longitudinal shrinking ($\partial c/\partial s < 0$)	Normal to the streamlines
Diverging streamlines ($\partial\alpha/\partial n > 0$)	Normal to the streamlines
Converging streamlines ($\partial\alpha/\partial n < 0$)	Along the streamlines
Cyclonic shear ($\partial c/\partial n > 0$)	45° to the right of the streamlines
Anticyclonic shear ($\partial c/\partial n < 0$)	45° to the left of the streamlines
Cyclonic curvature ($K_s > 0$)	45° to the left of the streamlines
Anticyclonic curvature ($K_s < 0$)	45° to the right of the streamlines

$$\tan 2\theta = (cK_s - \partial c/\partial n)/(\partial c/\partial s - c\,\partial\alpha/\partial n) \qquad (15)$$

and

$$\partial u_1/\partial x_1 - \partial v_1/\partial y_1 = (\partial c/\partial s - c\partial\alpha/\partial n)\sec 2\theta + (cK_s - \partial c/\partial n)\csc 2\theta \qquad (16)$$

Positive deformation from (15) implies the axis of dilatation makes an angle θ with the streamline. Negative deformation from (15) indicates the axis of dilatation makes an angle $\theta \pm 90°$ with the streamline.

The effect of each of the four kinematic components in the right side of (15) in determining the resultant direction of dilatation is summarized in Table 1. In most conditions several of these individual components are operating, and the resultant direction can be found by giving to each component direction its proper weight.

Using Table 1 as a guide, it is possible to interpret some of the more prominent features of Figures 6ef directly from the wind analysis of Figure 6b. In the extreme northwest part of the pattern along the current axis and upstream from the strongest winds there is very little shear, curvature, or streamline divergence, but the rapid longitudinal stretching (downstream increase of wind) places the axis of dilatation very nearly along the streamlines. Near 40° latitude and 90° longitude there is rapid longitudinal shrinking (downstream decrease of wind) and some streamline divergence, while the shear and curvature components appear small. The net result is contraction along the streamlines, or dilatation normal to the streamlines, as indicated by the shafts in Figure 6f. On the right flank of this wind maximum facing downstream there are several places where the stretching deformation seems small, but the relatively strong anticyclonic shear and the cyclonic curvature combine to place the dilatation axis about 45 degrees to the left of the wind. Observe the opposite appears to be the case on the left side of the wind maximum where cyclonic shear predominates. Observe also how the actual flow in regions of strong deformation differs markedly from the elementary pattern of deformation about a point (Fig. 2).

Planimetric evaluation of deformation--Horizontal divergence at any level can be measured approximately from the time change in area of the triangle outlined by three air parcels. These three parcels located at the same level are moved with their (instantaneous) winds through a selected time interval δt. The difference in area between the final and initial triangles is δA, and the average divergence over the triangle is then

$$\partial u/\partial x + \partial v/\partial y \approx (1/A)\ \delta A/\delta t$$

where A is the area of the initial triangle (outlined by the observing stations). If the winds are all rotated 90° to the right, application of this same procedure gives the average vorticity with similar approximation. BELLAMY [1949] has described a convenient nomogram for measuring divergence and vorticity in this way.

This method can be adapted to measurement of deformation from three wind reports. Each of the winds is rotated so that the resulting vector u'', v'' is related to the actual wind vector u, v in the following manner

$$u'' = u \qquad v'' = -v$$

This change is merely one of reversing the sign of the v component. The orientation of the initial coordinates is arbitrary, but the same coordinate system will have to be used throughout the entire process for each set of three winds. The divergence of the new vectors is

$$\partial u''/\partial x + \partial v''/\partial y = \partial u/\partial x - \partial v/\partial y$$

and is equal to the stretching deformation for the actual winds.

A second set of vectors is now chosen satisfying the following relation to the actual winds

$$u'' = v \qquad v'' = u$$

The divergence of these vectors is

$$\partial u''/\partial x + \partial v''/\partial y = \partial v/\partial x + \partial u/\partial y$$

and is equal to the shearing deformation for the actual winds. After both types of deformation have been evaluated, the resultant rate and direction of deformation are found by methods described previously.

The geostrophic deformation--A useful method for measuring and especially for visualizing the horizontal deformation on a routine basis is provided by the geostrophic approximation. Its validity will be proportional to the agreement between geostrophic and actual wind.

The component geostrophic equations may be expressed by

$$u_g = -(980/f)\ (\partial Z/\partial y)_p \qquad v_g = (980/f)\ (\partial Z/\partial x)_p$$

where Z is the geopotential height of a pressure surface (in units $cm^2\ sec^{-2}$), $f = 2\omega \sin\phi$ is the Coriolis parameter, 980 is a dimensionless constant, the subscript p denotes differentiation at constant pressure, and the x,y system is arbitrary in the horizontal plane. If we now differentiate these equations each with respect to x and y, we obtain

$$\partial u_g/\partial x = -(980/f)\ (\partial^2 Z/\partial x \partial y)_p - (u_g/f)\ \partial f/\partial x$$

$$\partial v_g/\partial y = (980/f)\ (\partial^2 Z/\partial x \partial y)_p - (v_g/f)\ \partial f/\partial y$$

$$\partial u_g/\partial y = -(980/f)\ (\partial^2 Z/\partial y^2)_p - (u_g/f)\ \partial f/\partial y$$

$$\partial v_g/\partial x = (980/f)\ (\partial^2 Z/\partial x^2)_p - (v_g/f)\ \partial f/\partial x$$

The quantities on the left are strictly the variation of motion in a constant pressure surface, for example, $(\partial u_g/\partial x)_p$ instead of the horizontal variation, and the deformation obtained is at constant pressure instead of horizontal deformation.

The stretching and shearing geostrophic deformations are then

$$\partial u_g/\partial x - \partial v_g/\partial y = -2(980/f)(\partial^2 Z/\partial x \partial y)_p - (1/f)\,(u_g\,\partial f/\partial x - v_g\,\partial f/\partial y) \quad \dots\dots\dots \quad (17)$$

$$\partial v_g/\partial x + \partial u_g/\partial y = (980/f)\,(\partial^2 Z/\partial x^2 - \partial^2 Z/\partial y^2)_p - (1/f)\,(v_g\,\partial f/\partial x + u_g\,\partial f/\partial y) \quad \dots \quad (18)$$

If we neglect the terms involving the variation of the Coriolis parameter, then following (7)

$$\tan 2\theta \simeq -\left[(\partial^2 Z/\partial x^2 - \partial^2 Z/\partial y^2)/\,2\,\partial^2 Z/\partial x \partial y\right]_p \quad \dots\dots\dots\dots \quad (19)$$

and from (9)

$$\partial u_{g1}/\partial x_1 - \partial v_{g1}/\partial y_1 \simeq -2\,(980/f)\,(\partial^2 Z/\partial x \partial y)_p \sec 2\theta \simeq (980/f)\,(\partial^2 Z/\partial x^2 - \partial^2 Z/\partial y^2)_p \csc 2\theta \quad (20)$$

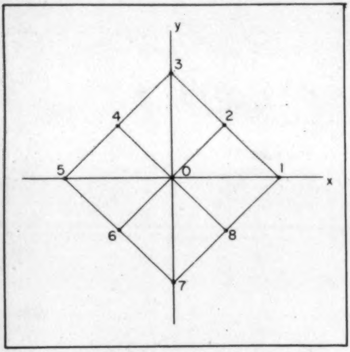


Fig. 7--Grid for computing geostrophic deformation

The geostrophic deformation can be evaluated graphically from the heights of a pressure surface read at certain points in a grid system such as illustrated in Figure 7. If the diagonal distance across the smaller squares is δs, it can be shown that

$$(\partial^2 Z/\partial x^2)_p \approx (Z_1 + Z_5 - 2\,Z_0)/(\delta s)^2$$

$$(\partial^2 Z/\partial y^2)_p \approx (Z_3 + Z_7 - 2\,Z_0)/(\delta s)^2$$

$$(\partial^2 Z/\partial x \partial y)_p \approx (Z_2 - Z_4 + Z_6 - Z_8)/(\delta s)^2$$

Equation (19) then becomes

$$\tan 2\theta \approx -(1/2)[(Z_1 - Z_3 + Z_5 - Z_7)/(Z_2 - Z_4 + Z_6 - Z_8)]$$

and (20) becomes

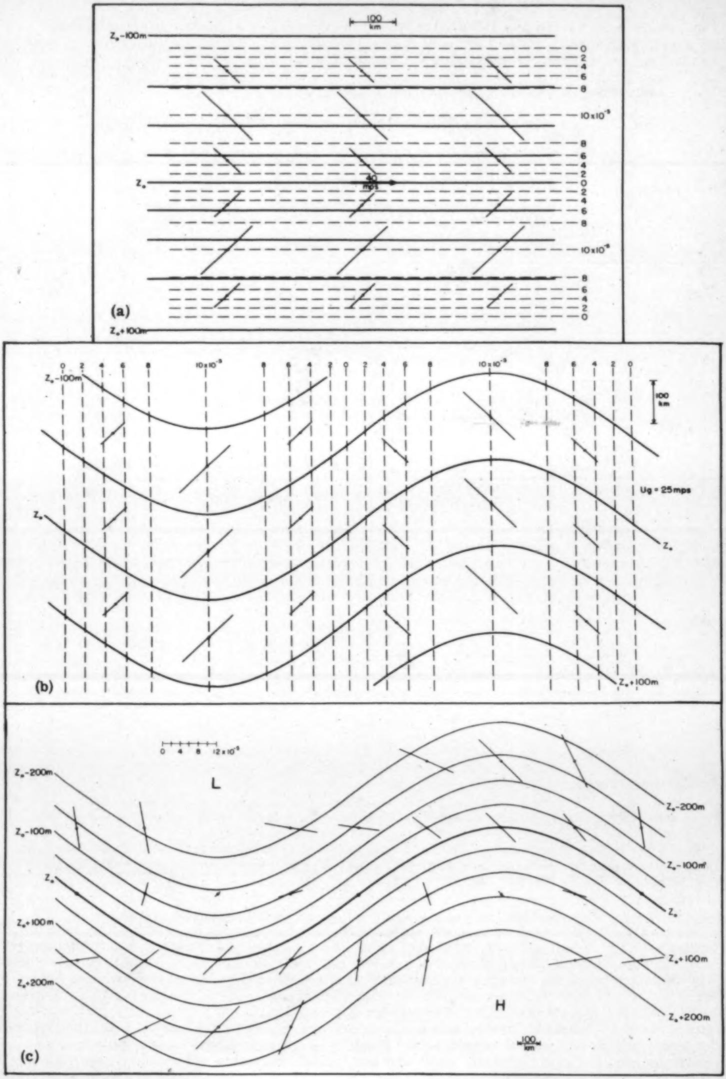
$$\begin{aligned}\partial u_{g1}/\partial x_1 - \partial v_{g1}/\partial y_1 &\approx 2[980/f(\delta s)^2\,(Z_2 - Z_4 + Z_6 - Z_8) \sec 2\theta \\ &\approx 980/f(\delta s)^2\,(Z_1 - Z_3 + Z_5 - Z_7) \csc 2\theta\end{aligned}$$

It is also found that

$$\left|\partial u_{g1}/\partial x_1 - \partial v_{g1}/\partial y_1\right| \approx [980/f(\delta s)^2]\,\sqrt{(Z_1 - Z_3 + Z_5 - Z_7)^2 + 4(Z_2 - Z_4 + Z_6 - Z_8)^2}$$

The deformation determined from these equations apply to the central point about which the data are taken, that is, the point 0 in Figure 7. The angle θ is measured from the diagonal 5, 0, 1. The grid system can be fixed on the map, or it can be shifted relative to the map to any desired location and direction.

From (19) and (20) the geostrophic deformation was determined in each of the four idealized pressure patterns shown in Figure 8, in each of which was assumed a constant value $f = 0.98 \times 10^{-4}$ sec.$^{-1}$. In Figure 8a the deformation is due only to the shear. Anticyclonic shear gives dilatation 45° to the left of the wind, and cyclonic shear 45° to the right of the wind. The important feature brought out by this diagram is the large deformation occurring in straight shearing flow. Figure 8b shows the effects of curvature on the deformation in a non-shearing sinusoidal flow pattern. Figure 8c combines both shear and curvature in a sinusoidal pattern. The deformation is greatest where anticyclonic shear and cyclonic curvature act together to the right of the current center in the pressure trough, and where cyclonic shear and anticyclonic curvature act together to the left of


100 km
Z₀-100m
0
2
4
6
8
10x10⁻³
8
6
4
2
0
40 mps
Z₀
2
4
6
8
10x10⁻³
8
6
4
2
0
Z₀+100m
(a)
0 2 4 6 8 10x10⁻³ 8 6 4 2 0 2 4 6 8 10x10⁻³ 8 6 4 2 0
Z₀-100m
100 km
Ug = 25mps
Z₀
Z₀+100m
(b)
0 4 8 12x10⁻³
L
Z₀-200m
Z₀-100m
Z₀
Z₀+100m
Z₀+200m
H
100 km
(c)

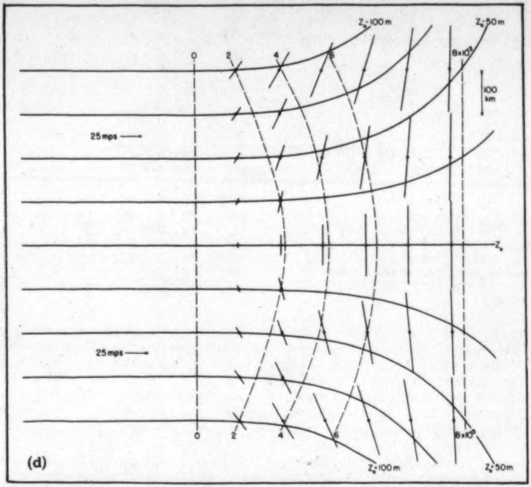


Fig. 8--The geostrophic deformation in certain idealized fields of motion; contours of the pressure surface are shown by heavy continuous lines

the current center in the pressure ridge. The pattern of deformation in a region of diverging or "difluent" streamlines is illustrated by Figure 8d. In a region of converging or "confluent" streamlines, the axis of dilatation would be more nearly parallel to the flow. The essential parts of the deformation pattern about a point of maximum wind speed can be derived from Figure 8. Downstream from the maximum wind the axis of dilatation is normal to the wind direction, upstream it is along the wind direction, to the left of the wind at the center it is 45° to the right of the wind, and to the right of the wind at the center it is 45° to the left of the wind. Past emphasis on deformation has been directed to neutral points in the wind field, or to the corresponding "cols" in the pressure field, characterized by flow resembling the patterns in Figure 2. Here we have avoided mention of such flow patterns only because the deformation is usually small compared to the deformation associated with stronger wind currents. Equation (16) shows quite definitely that deformation is proportional to wind speed and to horizontal variation of wind speed. In "col" areas both are small.

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WAVE RUN-UP ON SLOPING STRUCTURES

Kenneth N. Granthem

Abstract--Relationships have been developed from laboratory experiments which show the effect of side slope, wave steepness (H/L), relative depth (d/L), and the structure porosity on wave run-up. Maximum wave run-up occurs, for the range of angles examined, at approximately 30°. As the wave steepness (H/L) increases, the wave run-up increases, and as the relative depth parameter (d/L) decreases, the wave run-up increases. The wave approach was restricted to the direction perpendicular to the axis of the structure.

Introduction--This investigation was conducted for the purpose of determining experimentally the effect of side-slope angle and structure porosity on wave run-up. Wave run-up on sloping structures is important in the problem of slope protection in such structures as breakwaters, earth dams, and levees, which are exposed to wave action. A large amount of energy is released when a wave peaks up, breaks, and runs-up on the sloping structure. This energy becomes apparent in the vertical rise of water and in the damage caused to sections of the sloping surface which are inadequately protected above the minimum wave run-up elevation.

A particular case of major importance is a breakwater constructed for the purpose of quieting the surface of the water in the lee of the breakwater. As this study shows, if proper angles of side slope are not used in the design, wave run-up may become great enough to overtop the structure and cause large disturbances in the "protected" area.

To determine the factors influencing wave run-up, a model study was conducted in the wave channel in the Hydraulics Laboratory at the University of California [GRANTHEM, 1953]. The results of this study are discussed below.

Laboratory equipment--The experimental equipment consisted of the glass-walled wave channel shown in Figure 1. Also shown in this figure are the definitions of the terms wave run-up, R; wave height, H; wave length, L; water depth, d; slope angle, ϕ; and the porosity, n. The bottom profile of the channel gave an effect of waves being propagated from deep water into shallow water (where $d/L < 0.5$). The channel was one foot wide, three feet high, and 60 ft long, with a wave

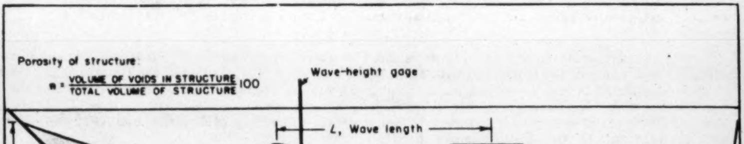

Fig. 1--Diagrammatic sketch of wave channel generator at one end and a model structure at the other end. A two-channel Brush recorder recorded the water surface-time history by means of wire resistance elements [MORISON, 1949].

The models which were used consisted of (1) a smooth flat surface with a porosity n = 0 pct, (2) a specially constructed box 6 ft long by 0.83 ft wide by 0.30 ft deep filled with 1 1/2-inch maximum angular stone with a porosity n = 32.6 pct, and (3) the same box filled with a well-rounded pea gravel with a porosity n = 28.9 pct. Slope changes by erosion were prevented in Models (2) and (3) by means of wire netting across the exposed slope surface.

Experimental procedure--The experimental procedure involved three steps: (1) Generate waves for each run, of given periods and heights, and record the surface-time history of the waves on a Brush recorder; this was essentially a calibration of the wave channel without a structure in place. (2) Install the smooth-surface type of structure. (3) Keep depth, period, and wave height constant, and vary the side-slope angle of the structure for each run; the wave run-up on the structure was measured using waves which had the same amplitude, period, and length as waves in the

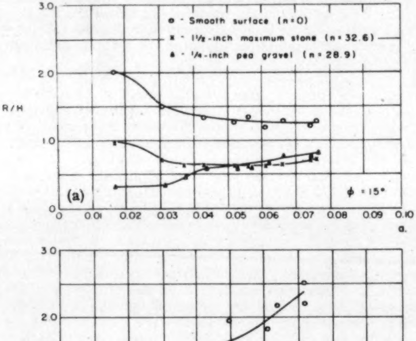

Fig. 2--Wave run-up as a function of wave steepness and porosity of structure for slope angles of 15, 30, and 45° with a constant relative depth, d/L = 0.218

original calibration of the wave channel (Step 1). (Wave run-up was defined, and measured, as the distance from the still-water level to the point where the entire face of the structure was wetted. Spray resulting from breaking waves, which progressed past the point of wave run-up, was not included in the measurement.) (4) Repeat Step 3 with a new period and wave height. (5) Measure wave run-up, with slope of structure constant, and varying the wave steepness, (H/L). This investigation was repeated for angles of 15, 30, and 45°. (6) Measure wave run-up with slope angle of structure and wave steepness, (H/L), constant and varying the relative depth, (d/L). This investigation was completed only for the angle of 30°. (7) Steps 3, 4, 5, and 6 were repeated for each type of stone structure.

In each run, a series of about ten waves was recorded before wave reflections from the structure confused the record. The wave run-up on the structure was measured during the time when these initial waves were impinging on the structure. The wave machine was stopped after the wave run-up was measured, and the water was allowed to become quiet. The run then was repeated. Each run was repeated at least three times.

Consistency was maintained between runs and between measurements on different types of structure by the surface-time history of the waves recorded on the Brush recorder. By observation of the surface-time history of the waves, it was found that the reflected energy of the waves did not appear in the record until approximately after the ninth or tenth wave had impinged upon the structure.

Experimental results--In order to determine the effect of the wave steepness, (H/L) on wave run-up, tests were made on the three model structures mentioned above (porosity n = 0 pct, porosity n = 28.9 pct, and porosity n = 32.6 pct) over a relatively large range of values of steepness. The angle of slope of the structure was maintained constant for each range of H/L and for each type of structure (Fig. 2). This condition was investigated for three different angles, 15, 30, and 45°. Figures 2b and 2c show that for the angles of 30 and 45° there is an increase in wave run-up for increasing values of $H/L > 0.03$. It is apparent from examination of these curves that there is a great advantage in having structures with high roughness coefficients and with relatively large porosity. There is a large percentage decrease in wave run-up, for the same energy dissipation on the structure, when the porosity is large. It is apparent from the curves that the freeboard needed to prevent overtopping of a structure is much greater for the condition of a smooth surface than for the condition of high porosity. Undoubtedly the irregularity of the curves shown in Figures 2, 3, and 4, especially with the lower values of H/L, is due to friction effects as the waves rush up the slopes. Of interest in this connection are the recent studies of BRUUN [in press] wherein wave reflections were measured at structures which were given various degrees of rectangular roughness as previously studied by JOHNSON [1944]. Other recent studies on wave run-up have been conducted at the WATERLOOPKUNDIG LABORATORIUM [1952] in Holland.

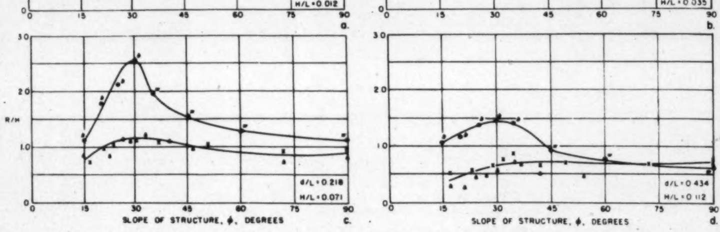

Fig. 3--Relationship between wave run-up and slope

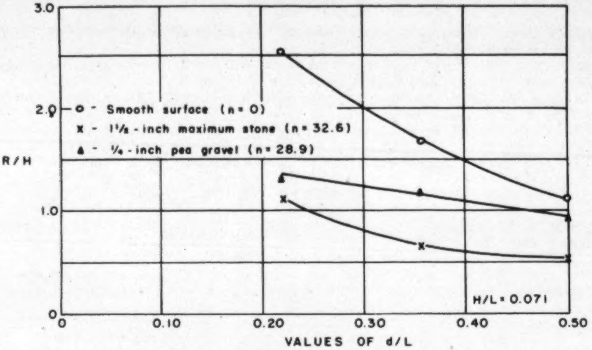

Fig. 4--Relationship between wave run-up and relative depth for a constant wave steepness and a slope angle of 30°

The diagrams shown in Figure 3 were obtained in order to show the effect of the slope angle on wave run-up for a large range of relative depth, d/L. Experiments were performed on the three model structures (n = 0 pct, n = 28.9 pct, and n = 32.6 pct) over a range of angles from 15 to 90°. The relative depth, (d/L), and the wave steepness, (H/L), were maintained constant for each angle. The results are consistent in that the maximum value for wave run-up occurs in the vicinity of 30° for each set of experiments. It is significant to note that there is a decrease in wave run-up for angles both smaller and larger than 30°. This fact is important in structures where wave run-up is a major problem. From current literature [JOHNSON, 1950], it is the consensus that the slope angle should be within the range of 1/1.5 to 1/1.75, which unfortunately very closely approximates 30°.

Note in Figure 3a, where d/L and H/L were small, that there was a relatively large run-up on the smooth structure for small slope angles. These waves simply "surged" up the structure surface without breaking. For increasing values of H/L and d/L, larger amounts of energy were dissipated by the waves breaking on the structure. For all tests other than noted in Figure 3a, the waves were consistent in that they all broke on the structure up to the "critical" angle of 30°; above 30° the wave "surged" up the slope without breaking, and there was an obvious decrease in run-up. As the angle of slope increased there was an increase in reflected wave energy; consequently, there was a decrease in run-up.

Figure 4 was prepared to show the effect of the relative depth (d/L) on wave run-up. For this particular investigation the slope angle was maintained constant for a large range of values of d/L. The wave steepness (H/L) also was maintained constant. The range of values for d/L covered extremes from a very small value to a value approaching the deep-water ratio of 0.5. In all cases, for an increasing value of d/L, there was an obvious decrease in run-up for the same amount of energy dissipation on each type of structure.

Conclusions--This investigation indicates that (1) structure porosity has a major effect upon wave run-up; (2) the primary variables affecting wave run-up are wave steepness, relative depth, angle of side slope, and porosity of the structure; for values of increasing wave steepness (for $H/L > 0.03$) there is an increase in wave run-up; for decreasing values of d/L there is an increase in wave run-up; (3) the critical point of side-slope angle appears to be approximately 30°. Any variation from this slope, in either direction, probably will decrease wave run-up, other factors being equal.

Acknowledgment--The author appreciates the suggestions of J. W. Johnson in conducting this investigation.

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A THEORETICAL EXAMPLE OF WIND-INDUCED CIRCULATION IN A SEMICIRCULAR CANAL

N. P. Fofonoff

Abstract--The steady-state stream function for the vertical circulation produced by a uniform horizontal wind stress on the surface of a canal of semicircular cross-section is derived analytically. The streamlines have been calculated and a comparison is made with some experimental results obtained by Hidaka and Koizumi in 1950 using a thin elastic-plate model.

Introduction--The problem considered in this paper is that of determining the circulation in the vertical plane of a body of water having a homogeneous density filling a canal or elongated pond whose bottom profile is known. The circulation is produced by a known wind stress on the water surface. The inertial and Coriolis forces are neglected and the mean motion is assumed to be characterized by constant, isotropic mixing coefficients. The wind is assumed to be steady and to have persisted long enough for a steady state in the mean circulation to have been established. The stream function of the circulation then satisfies, in the linear approximation, the same differential equation and boundary conditions as, and is proportional to, the function giving the small vertical deflections of a thin plate of uniform flexural rigidity clamped horizontally in the profile of the canal bottom, the deflections being produced by a bending moment proportional to the wind stress applied along a hinged straightedge representing the water surface.

HIDAKA and KOIZUMI [1950] have used the thin-plate model to determine the stream function of the vertical circulation in canals of various cross-sections for several different distributions of wind stresses. Their model is useful because analytical solutions for the stream function are difficult to obtain except for canals with boundaries of a very special type. TAKEGAMI [1934] has calculated the theoretical stream function for a rectangular canal assuming a constant wind stress. Later, HIDAKA [1939] extended Takegami's work by considering the inertial terms.

An exact solution in closed form, neglecting inertial and Coriolis forces, for the stream function is given in this paper for a canal of semicircular cross-section and a constant wind stress transverse to the axis of the canal. The solution is compared with the stream function obtained experimentally by HIDAKA and KOIZUMI [1950] using their thin-plate model.

Formulation of the problem--The canal cross-section is chosen to be a semicircle of radius a. A rectangular coordinate system is chosen with the origin at the center of the horizontal diameter of the semicircle. The coordinate x is measured horizontally and is taken to be positive in the direction of the wind, and the coordinate y is taken positive downwards. The hydrodynamic equations are converted into dimensionless form by introducing the parameters

$$\xi = x/a \qquad \eta = y/a \qquad \phi = \psi/\psi_o$$

where ψ is the stream function, ψ_o is the total volume of water in circulation per unit time per unit length of the canal, and a is the radius of the semicircular canal. It is also convenient to introduce the polar coordinates (r, θ) in dimensionless form

$$p = r/a = (\xi^2 + \eta^2)^{1/2}, \theta = \tan^{-1} y/x$$

The mathematical problem is then to find ϕ so that $\nabla^2 \nabla^2 \phi = 0$, where $\nabla^2 = \partial^2/\partial\xi^2 + \partial^2/\partial\eta^2$, subject to the boundary conditions along the water surface, approximated by $\eta = 0$

Condition (a) $\phi = 0$

Condition (b) $\partial^2 \phi/\partial\eta^2 = -\kappa t(\xi)$

where $\kappa = \tau a^2/A\psi_o, \tau t(\xi)$ is the wind stress at $\xi = x/a$, and A is the eddy viscosity, and the boundary conditions along the canal bottom, p = 1

Condition (c) $\phi = 0$

Condition (d) $\partial\phi/\partial p = 0$

Solution of the problem--The function ϕ is chosen so that the boundary conditions along the surface ($\eta = 0$) are satisfied. This may be done by choosing ϕ of the form

$$\phi = -(1/2)\,\kappa\,\eta\,\mathrm{Re}\left\{T(\omega)\right\} + \sum_{n=1}^{\infty}\left\{A_n p^{n+2} + B_n p^n\right\}\sin n\theta$$

where $\omega = \xi + i\eta$, and $i\,dT/d\omega = t(\omega)$, where $t(\omega)$ is obtained by replacing ξ by ω in (b). The function ϕ is a solution of the homogeneous biharmonic equation and contains two sets of arbitrary coefficients A_n, B_n required to satisfy the boundary conditions (c) and (d) along the canal bottom ($p = 1$). These boundary conditions lead to a pair of simultaneous equations which determine A_n and B_n. The sum of the resulting series may be found explicitly in many cases by considering the imaginary part of the sum function obtained by substituting ω^n for $p^n \sin n\theta$ and summing the power series in ω.

In the simplest case the wind stress is taken to be constant over the canal surface, that is, $t(\xi) = 1$. Then

$$\phi = -(1/2)\,\kappa\,p^2\sin^2\theta + \sum_{n=1}^{\infty}\left\{A_n p^{n+2} + B_n p^n\right\}\sin n\theta$$

The coefficients A_n and B_n, determined by Fourier analysis, are

$$A_n = (2\kappa/\pi)\left\{1/n\,(n+2)\right\}$$

$$B_n = -(2\kappa/\pi)\left\{1/(n^2-4)\right\} \quad \text{for n odd}$$

$$A_n = B_n = 0 \quad \text{for n even}$$

The series may be summed explicitly to give

$$\phi = -(1/2)\,\kappa\,p^2\sin^2\theta + (\kappa/2\pi)\Big\{[(1-p^2)/p]\sin\theta + 2\,p^2\sin^2\theta\tan^{-1}[2\,p\sin\theta/(1-p^2)] - \frac{(1-p^2)^2}{2\,p^2}\left[\frac{\sin 2\theta}{2}\log_e\left(\frac{1+2\,p\cos\theta+p^2}{1-2\,p\cos\theta+p^2}\right) - \cos 2\theta\tan^{-1}\left(\frac{2\,p\sin\theta}{1-p^2}\right)\right]\Big\}$$

This function may be shown to be a solution by direct substitution into the biharmonic equation.

The pressure distribution can be calculated once the stream function has been determined. It is found that the pressure is not constant along $\eta = 0$, but is given by

$$P_{\eta=0} = P_o + 4\tau/\pi\left\{(1+\xi^2)/2\xi\,\log_e[(1+\xi)/(1-\xi)] - 1/\xi\right\}$$

This may be interpreted to mean that in the steady state the water surface cannot be horizontal but is given to the first approximation by

$$y_{\text{surface}} = (4\tau/\pi\rho g)\left\{(1+\xi^2)/2\xi\,\log_e[(1+\xi)/(1-\xi)] - 1/\xi\right\}$$

where τ is the surface stress due to the wind, ρ is the density of the water, and g is the acceleration of gravity. This formula gives a surface slope of $16\tau/3\pi\rho g a$ at the center of the canal. The logarithmic singularities in the pressure at the corners of the semicircular canal $\xi = \pm 1$ indicate that the linear approximation is not valid at these points.

Comparison with experimental results--Contours of ϕ, normalized to an arbitrary ϕ_{max}, are plotted in Figure 1. Figures 2 and 3 show profiles of the theoretical and experimental stream functions, normalized to unity at their maxima, plotted along the radii $\theta = 90°$ and $\theta = 45°$ or $135°$. The model used by HIDAKA and KOIZUMI [1950] gives a good picture of the functional form of the stream function as can be seen from the diagrams. The stream function as defined in this paper has the maximum value of approximately $0.0277\,\kappa$. Hidaka and Koizumi, however, do not give experimental data with which this maximum value may be compared.

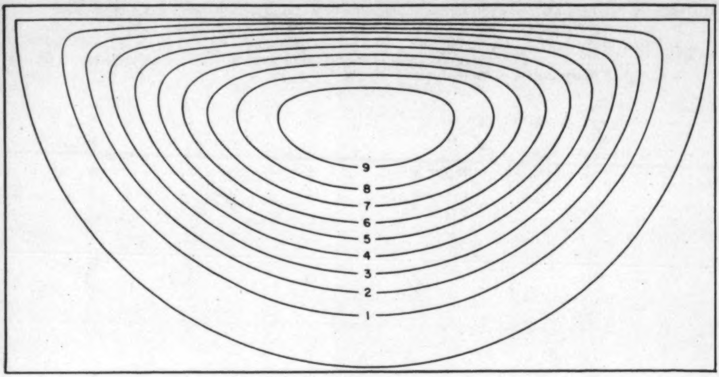

Fig. 1--Streamlines of the circulation for a constant wind stress, normalized to arbitrary units

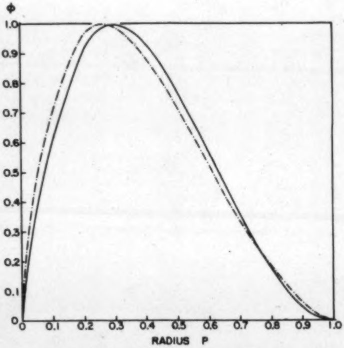

Fig. 2--Profiles of the theoretical stream function (solid curve) and the experimental stream function (dashed curve), normalized to unity at their maxima, compared along the radius $\theta = 90°$

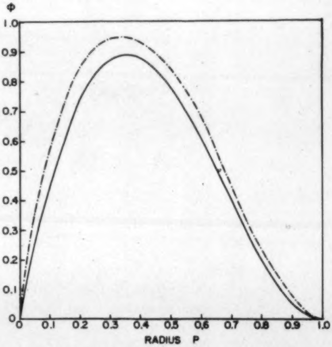

Fig. 3--Profiles of the theoretical and experimental stream functions, with the same normalization as in Figure 2, compared along the radius $\theta = 45°$ or $135°$

Acknowledgment--The author wishes to thank the National Research Council of Canada for a scholarship (1951) which enabled him to carry out this work.

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SOME EFFECTS OF THE DIVERSION OF THE SANTEE RIVER ON THE WATERS OF CHARLESTON HARBOR

Bernard D. Zetler

Abstract--Surface temperature and density observations in Charleston Harbor indicated a sharp decrease in salinity beginning in 1942. It was at this time that a hydro-electric plant began diverting some of the waters from the Santee River into the Cooper River which flows into Charleston Harbor. Long-period tide observations at Charleston and at other places along the Atlantic Coast were examined to detect related changes in sea level and range of tide. They indicate that about 0.09 ft of the rise in sea level in Charleston Harbor can be attributed to the diversion of the Santee River and that the tidal range may have been increased about 0.05 ft.

In the early part of 1942 the hydro-electric plant near Moncks Corner, South Carolina, began diverting large quantities of water from the Santee River into the Cooper River which flows into Charleston Harbor. The subsequent tide, temperature, and density observations made by the U. S. Coast and Geodetic Survey indicate that significant changes have occurred in the waters of Charleston Harbor. The large change in density made it quickly apparent that the salinity of the surface waters in Charleston Harbor had been considerably diminished [U. S. COAST AND GEODETIC SURVEY, 1949]. Now that ten years have gone by since the change, it appears that the height of sea level and the range of tide may also be affected.

The tide gage in Charleston Harbor is located on the Custom House Wharf, about five miles from the open sea. The tide gage furnishes a continuous graph of the rise and fall of the tide, with time as one coordinate and the height of tide as the other. During his daily visit to the gage, the tide observer determines the temperature and density of a sample of water drawn by bucket from near the surface [U. S. COAST AND GEODETIC SURVEY, 1941].

The density reading is obtained by using a hydrometer. Since the observed density of a given sample of water will vary according to the water temperature, the density is reduced to its equivalent value for a standard temperature of 15°C (59°F). It is thereby possible to compare or average the densities on different days even though the water temperatures on those days vary considerably. The densities reduced to 15°C can be readily converted into equivalent salinities.

Figure 1 shows annual salinity of the surface water in Charleston Harbor. While there are sharp changes from year to year, it is readily apparent that the series through 1941 and the series

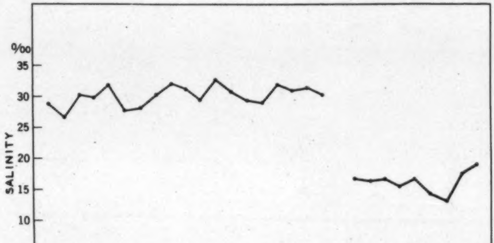

Fig. 1--Annual salinity of surface water of Charleston Harbor, 1923-1951 beginning in 1943 represent completely different conditions, the latter being more than a 40 pct decrease in salinity. The year 1942 is omitted even though obserservations are available, since the change in river flow took place during this year and the annual mean therefore contains both conditions.

The changes in sea level and range are more subtle and require long series at a number of nearby stations for comparison purposes. Figure 2 shows annual sea level observed at Charleston, Baltimore, and Mayport. Despite sharp fluctuations both upward and downward from year to year, it is apparent that sea level at Charleston has risen from a fourth to a half foot during 30 years. However, it has been well established that sea level has been rising slowly along our entire Atlantic Coast during this period. Various statistical procedures have been used to iron out the year-to-year changes in determining a long-period trend, and it is estimated that the present rate of rise along most of the East Coast of the United States is about 0.02 ft/yr [MARMER, 1951b].

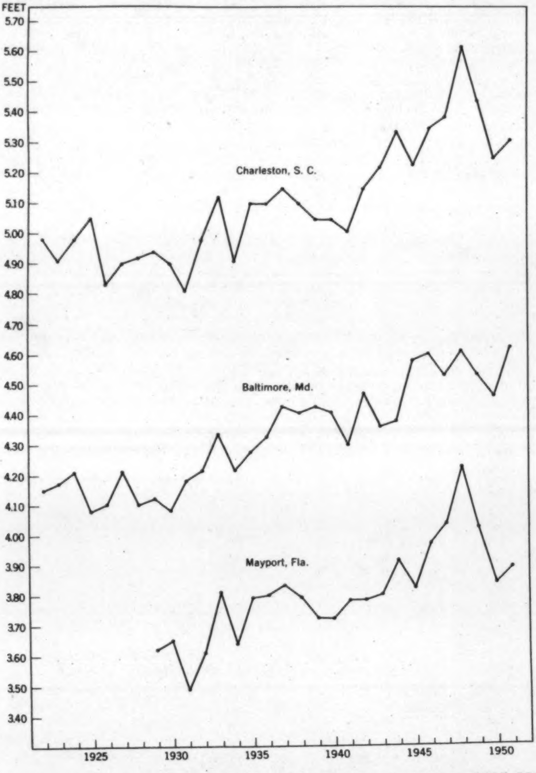

Fig. 2--Annual mean sea level at three Atlantic Coast stations, 1922-1951 (heights are referred to zero of tide staff at each station)

It should be noted that the observed rise in sea level is a relative comparison of land and sea levels. It could be caused by an increased supply of water along the Coast, a subsiding of the land mass, or a combination of both. Various theories have been proposed to support one or the other hypothesis, but none has been conclusive. Furthermore, one cannot project the trend into a prediction for the future. What we are observing may be a cyclical change which could reverse itself at any time, or it may continue and possibly accelerate.

In view of this known rise in sea level all along the Coast, a comparison of the change was made with other tide stations both north and south of Charleston. Since few stations have as long a series, the longest possible series was used for each available station. The identical series was applied to Charleston values for each comparison. Table 1 shows average sea level for each comparative station and Charleston for the available period through 1941 and average sea level for the following ten years. The amount of increase in sea level from the first epoch to the second is shown for each station in column (3). Column (4) indicates that in each comparison the rise in sea level is greater at Charleston. Furthermore, the difference is remarkably consistent between 0.07 and 0.10 ft. The increased river discharge presumably caused a higher river gradient extending to a point near the estuary entrance. There was a further increase in slope due to the decreased density of the upper layers of the river. At the Charleston tide gage, there was a total rise in sea level of about 0.09 ft.

Table 1--Comparison of rise in sea level[a]

Tide stations	Average		Average sea level, 1942-1951 (2)	Increase in sea level (3)	Charleston increase (4)
	Period	Sea level (1)			
		ft	ft	ft	ft
Charleston, S. C.	1932-1941	5.06	5.33	0.27	. . .
Miami Beach, Fla.	1932-1941	3.45	3.62	0.17	0.10
Charleston, S. C.	1929-1941	5.02	5.33	0.31	. . .
Mayport, Fla.	1929-1941	3.71	3.93	0.22	0.09
Charleston, S. C.	1933-1941	5.07	5.33	0.26	. . .
Southport, N. C.	1933-1941	3.88	4.06	0.18	0.08
Charleston, S. C.	1922-1941	4.99	5.33	0.34	. . .
Baltimore, Md.	1922-1941	4.23	4.50	0.27	0.07
Charleston, S. C.	1923-1941	4.99	5.33	0.34	. . .
Atlantic City, N. J.	1923-1941	6.34	6.59	0.25	0.09

[a] Heights are referred to zero of tide staff at each station.

The change in range is relatively smaller but nevertheless interesting. The range of tide is subject to a cyclical change with a period of about 18.6 years, varying in accordance with the longitude of the Moon's node. Accordingly the observed range for any year is multiplied by a factor to correct it to a mean value [**MARMER**, 1951a]. The annual ranges in the following discussion are corrected values which have been obtained by multiplying observed ranges by their appropriate factors.

Ten-year averages of range of tide for Charleston, Mayport, Baltimore, and Atlantic City are given in Table 2. Compared to the 1932-1941 series, the range of the 1942-1951 series has increased at Charleston while it decreased at the other three stations. Judging just from these 20 years, one might conclude that this variation at Charleston should be attributed to the increased river flow, even though an increased river level will ordinarily result in a decreased range of tide. A comparison of the 1922-1931 series with the following 1932-1941 series creates some doubt as to the reliability of the above conclusion. Charleston and Baltimore agree well in their change from the first period to the second. However, Mayport and Atlantic City do not, and even though the Mayport value may be disregarded because it is based on only three years, the Atlantic City value is based on nine years and may not be readily discounted. We therefore conclude that the increased range at Charleston since 1942 diverges from the trend along the Coast, but, because of the small amount of change and a contradiction in the trend at Atlantic City during the earlier decades, the divergence is not necessarily related to the increased flow of the Cooper River.

Table 2--Range of tide[a]

Tide stations	Period		
	1922-1931	1932-1941	1942-1951
	ft	ft	ft
Charleston, S. C.	5.12	5.15	5.19
Mayport, Fla.	4.48[b]	4.48	4.46
Baltimore, Md.	1.10	1.14	1.12
Atlantic City, N. J.	4.09[c]	4.07	4.06

[a] All annual values have been corrected for the longitude of the Moon's node.

[b] Range for the period 1929-1931.

[c] Range for the period 1923-1931.

There was no significant change in either the surface-water temperature or the mean high-water lunitidal interval.

Longer series of observations at Charleston and other places would have facilitated a more complete analysis of these changes. On the basis of the available data, the increased fresh-water flow into Charleston Harbor has decreased its average surface salinity by over 40 pct, has raised sea level by about 0.09 ft, and may have increased the range of tide by about 0.05 ft. The rise in sea level combined with the increased range raises the planes of mean high water and mean low water 0.11 ft and 0.06 ft respectively.

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A LONG-PERIOD EFFECT OF TIDES ON FRASER RIVER STAGES

W. Douglas Baines

Abstract--The major floods which occurred in the Fraser system in 1948 and 1950 had a peak-discharge difference of 100,000 cfs, but the maximum river stage at Mission was nearly the same for both floods. One of the explanations advanced for this behavior has been thoroughly investigated on the Fraser River model. The phenomenon studied was that of the effect of tides on the mean stage of the river. This is not to be confused with the hourly rise and fall stages resulting from tides. It has been deduced that both the mean tide and the range of tide in the Strait of Georgia affect the river mean stage. Natural long-term variation in both of these quantities cause small variations in river stage. It is shown from the differential equation of motion that the second effect is a direct result of size of the non-linear term.

Introduction--The Fraser River, for most of its 790-mile length, is a fairly steep, swiftly flowing mountain river but near its outlet into the Strait of Georgia (see Fig. 1) it flows through a flat delta area. Throughout this delta and for a considerable distance upstream, effects of the tides are noticed. The water surface rises and falls in a manner similar to that of the Strait but with a time lag--as great as seven hours in the upper reaches. This tidal effect is not to be confused with the salt-water intrusion in the river which advances a comparatively short distance, as far as Steveston on the average.

In 1948, the Fraser River system experienced the biggest flood since 1894. There were two peaks to the flood about a week and a half apart. The discharge in the first peak at Hope, B. C., was 536,000 cfs, that in the second peak was 442,000 cfs. This flood caused serious damage all through the Fraser River valley, particularly near the town of Mission. The most serious con-

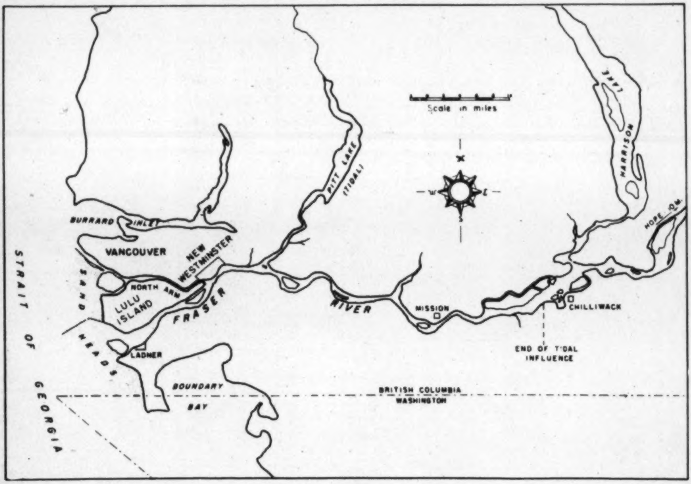

Scale in miles
N
W
E
S
PITT LAKE (TIDAL)
HARRISON LAKE
HOPE
BURRARD INLET
VANCOUVER
NEW WESTMINSTER
NORTH ARM
LULU ISLAND
FRASER RIVER
MISSION
CHILLIWACK
END OF TIDAL INFLUENCE
STRAIT OF GEORGIA
SAND HEADS
LADNER
BOUNDARY BAY
BRITISH COLUMBIA
WASHINGTON

Fig. 1--Lower Fraser River valley

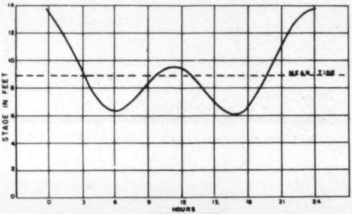
sequence at Mission was that the river stage did not drop appreciably (actually less than 0.2 ft) from the first peak to the second. This is quite surprising when it is realized that the channel from Mission to the Strait averages about 40 ft deep and is fairly straight and without sudden changes in cross section. In 1950, another major flood occurred. The discharge at Hope was 440,000 cfs and again the stage at Mission was about the same as it had been for all of the 1948 flood. The dyking system had been strengthened in the meantime so there was no serious damage. However, there is clearly an anomaly in the stage at Mission because it does not vary for discharges differing by as much as 100,000 cfs.

Several ideas have been advanced as to the cause of this anomaly. Briefly they are:

(1) As the flood wave moved from Hope to Mission, the flood hydrograph was flattened by the storage of water in the channel, in Harrison Lake, and behind the broken dykes. Unfortunately, this can not be definitely proven because there were no discharge measurements made at Mission during the flood periods. However, extensive calculations have been made on the storage possible in these areas and it has been concluded that the amount is not great enough to cause the effect at Mission.

(2) It has been reasoned that the first flood peak deposited sediment all through the river channels to such a depth that it could not be removed by the ensuing lower flows. If this were the case, then it is argued that the effect should be noticed even more strongly for lower flows for the reason that the Fraser River channels have steep banks and no side berms. Thus all material would have to be deposited in the bottom of the cross section. None of the extra deposits has been found and no stage anomaly has been noticed at discharges below 300,000 cfs. The only occasions when discharges above 300,000 cfs have occurred were during the two floods described above.

(3) The most abstruse suggestion as to the cause of the stage anomaly has been that either the tidal amplitude or the shape of the tide curve in the Strait was the cause of it. In the early summer, the tide in the Strait follows the trend illustrated by Figure 2 with a period of about two weeks. Starting with the small amplitude, of which June 23, 1950, is typical, the tidal range increases to a maximum (note June 30, 1950), and then decreases back to the small amplitude. The daily tide curves are unusual in that for the smaller amplitude tides the water surface is below mean level for a much longer period of time than in the larger. It has been reasoned that on days for which June 23, 1950, is typical, the water has more time in which to flow out and the velocities



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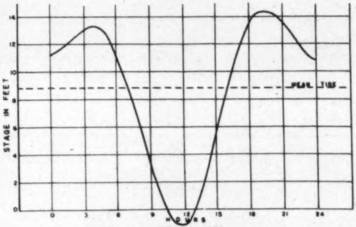

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Fig. 2--Tides in Strait of Georgia

are smaller (inference being that the friction effects are less). Hence the upstream stages should be lower than on days for which June 30 is typical. This reasoning agrees with the tides that actually occurred for the 1948 and 1950 floods. In the first 1948 peak, the tidal amplitude was small and during the second 1948 peak and the 1950 peak the amplitudes were large, the curves being very similar to the second curve in Figure 2.

Fraser River model investigations--The National Research Council (of Canada) built the Fraser River model at the University of British Columbia for the purpose of studying navigation improvements to the Fraser channels. As part of the model studies, the effect of tides on river stages has been investigated.

Two distinct long-period effects have been noted on the mean stages, that is, the average tide level over one cycle. The first of these effects is the result of variation of mean tide level in the Strait. During the summer, the mean level is constant except for an occasional variation of about 1/10 ft. In the winter, however, the storms in the Pacific Ocean will change the mean level by as much as two feet. These variations in the mean level are transmitted to the upper reaches of the river and appear to be undiminished as far upstream as the tidal influence is felt.

The model has shown the existence of the second long-term effect, that of the amplitude and shape of the tide curve. This is best illustrated by giving the results of a typical test wherein the tides of a period including June 23 and 30, 1950, were imposed on the model with a constant discharge of 440,000 cfs. These two days had the same mean level in the Strait but the stage at Mission was greater by the equivalent of 0.47 ft on June 30, 1950, the day with the greater tidal amplitude and the lesser time when the level was below mean. Thus there is a definite effect of either, or both, the amplitude or shape of the tide curve on the upstream stages. It is shown in the next section that both of these wave properties have an effect but these will be indistinguishable.

Mathematical discussion--A qualitative explanation for these long-period effects can be given by examining the equation of motion. For a straight, uniform channel, an approximation of the Fraser River, the equation is [GILCREST, 1950]

$$- S_0 + S_f = \partial y/\partial x + (V/g)\, \partial V/\partial x + (1/g)\, \partial V/\partial t \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where S_0 = channel bed slope = $\partial y_0/\partial x$ (S_0 inherently a positive quantity)
S_f = friction slope, if Chezy's form is used = $- V|V|/C^2R$
y = depth of flow at any cross section and instant
V = average velocity of flow over any cross section at any instant
x = distance along channel measured from seaward end
g = acceleration of gravity

The simple wave equation is often used as an approximation of (1). Assuming that $S_0 - S_f$ and the non-linear terms $(V/g)\, \partial V/\partial x$ are small compared to the other terms in (1), the wave equation results, namely

$$0 = \ y/\ x + (1/g)\partial V/\partial t \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

If (1) is integrated with respect to time over a tidal cycle from 0 to T and it is assumed that conditions at the end of the cycle are identical with those at the beginning, there results the form

$$dY/dx = - S_0 - (1/T) \int_0^T (V|V|/C^2R)\, dt - (1/T)\, d/dx \int_0^T (V^2/2g)\, dt \ldots\ldots\ldots (3)$$

where Y = mean stage = $(1/T) \int_0^T y\, dt$.

Two simple cases of flow are analyzed by means of (3) to illustrate its use. These are: (1) No motion. For this case $dY/dx = - S_0$. The solution of this gives the water surface as a horizontal line. (2) Wave equation approximations. The entire right-hand side of (3) reduces to zero for this case; this indicates that Y is a constant and the mean stage is parallel to the bed of the channel.

For the general case of an estuary, all terms in (3) must be considered. In the case of steady, uniform flow the first term, the bed slope, is the same size as the second term, the mean friction slope. However, in an estuary it is to be expected that the friction term, because of its variance similar to V^2, will be much greater than S_0. Besides this, the sign of the second term depends on the direction of flow. If the period of inflow were much longer than the period of outflow, then it would be positive. In the physical case, however, the length of outflow is always much greater than the inflow, so the mean friction slope will always be negative.

The third term is the velocity-head gradient. The integral is obviously positive because it is dependent on V^2. However, the gradient of the integral is always negative in an estuary because the tide influence decreases in the positive direction, that is, away from the sea.

The second and third terms are thus of the same sign, so their effects will always be felt together. This fact, in the light of the foregoing discussion, leads to the expectation that dY/dx will always be positive, that is, the mean stage increases in the direction away from the sea.

Comparing two different tide waves it is seen that

(1) If the difference between them is only in amplitude, the cycle with the larger amplitude will have the larger velocities associated with it. This will tend to increase both the second and third terms on the right-hand side of (3). Consequently, the mean stage should be greater for the cycle with the greater amplitude.

(2) If the difference between the tide cycles is in the length of time the water surface is below mean level, then it can be reasoned that greater instantaneous velocities will be associated with the cycle that has the shorter time. The equation of continuity enters into the reasoning and produces the result that whenever depths are small, velocities are large. The end effect is the same as in the first case.

Since the larger tidal amplitudes are accompanied by the shorter periods of time the water surface is below mean, the two effects cannot be separated in observations of the natural phenomena. In addition, the effects of the two variable terms on the right-hand side of (3) cannot be separated in any case since they always produce the same trend. So far the model results, as described in previous paragraphs, have verified the general conclusions reached from the theoretical reasoning but no quantitative verification has been attempted. An integration of (3) is now being performed with data obtained from the prototype. It is hoped by this means that some of the effects can be separated and their relative sizes evaluated.

Acknowledgments--In the preparation of this paper, the author made much use of the reports of the Dominion Provincial Board, Fraser River Basin; the discharge observations of the Water Resources Division, Department of Resources and Development; and the results from the Fraser River model of the National Research Council. Without the quantity and quality of the information from these sources, this paper would not have been possible. The author is grateful for the cooperation of these organizations.

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ON THE THERMAL CONDUCTIVITY OF SOIL, WITH SPECIAL REFERENCE TO THAT OF FROZEN SOIL

Akira Higashi

Abstract--Using the Angstrom principle, a new apparatus for measuring the thermal diffusivity of soil was designed. In order to give the sinusoidal boundary condition, the apparatus was constructed to change the applied voltage of a heater. A simple autotransformer and a special cam were used for this purpose. Using this apparatus, the thermal diffusivity of frozen soil as well as wet soil was measured. In the case of frozen soil, the samples were prepared under the conditions similar to natural frost formation. Thermal conductivity was computed from the diffusivity thus obtained and the volume specific heat of the soil. Moisture relationship of the thermal diffusivity and the thermal conductivity of frozen soils are represented by an empirical formula of exponential form. The formula holds only in the range of moisture content below the saturation. These relationships are shown graphically. Similar measurements were carried out with wet soil at room temperature. In nature, we often observe the segregation of ice in frozen soil. Such a frozen soil usually contains more water than that of saturation. Samples of various modes of segregation of ice were artificially prepared and their thermal diffusivity was measured. For the moisture ratio above saturation, the rate of increase of the thermal diffusivity with respect to moisture ratio is smaller than that expressed by the above formula. The variation of the thermal diffusivity of the frozen soil in relation to the direction of heat flow is comparatively small.

Introduction

From the geophysical point of view, it is important to know the value of thermal conductivity of soil as the function of its conditions. It is necessary for the calculation of heat exchange over the ground surface, the estimation of soil temperature at a certain depth, the determination of the depth of frozen soil, and so on. Among the various methods for measuring the thermal conductivity of soil, Angstrom's method is most useful, for it can be conveniently applied to the sample of soil in the state of natural packing. A new application of this principle designed in our Laboratory has proved to be very useful.

The investigation was chiefly carried out with respect to the thermal conductivity of frozen soil. As for the frozen soil, the preparation of the soil sample has an important meaning. The process for making samples adopted by the former investigators in this line seems to be far from the natural process of freezing of soil. Consequently, the structure of the sample is quite different from that of the natural frozen soil. For instance, the former samples were usually prepared by rapid refrigeration of soil in a container, in which the conductivity test was carried out. This sort of freezing process never takes place in nature.

In nature, freezing of soil proceeds from the surface vertically into the interior. According to the climatic conditions, the soil properties, and the water content of soil, various modes of soil frost take place. In our climate, in the frozen ground in winter, two modes of segregation of ice are usually observed in the frozen soil; (1) the ice plate of a considerable thickness, and (2) the dispersion of innumerable thin layers of ice embedded in the frozen soil. The ice plate is composed of a bundle of numerous ice filaments and is called an "ice filament layer." Three of these layers are seen in Figure 1 and two in Figure 2. The type of the dispersion of thin ice layers gives the appearance of a piece of sirloin beef, the ice layers corresponding to the fat layers and the frozen soil to the meat. This type may be tentatively called "sirloin-type freezing", one good example being shown in Figure 3. The description and classification of various modes of freezing of soil are given in the paper of NAKAYA and MAGONO [1940, 1942].

The segregation of ice in the frozen soil is very common in our climate. It is due to the abundance of water and the nature of soil. The soils in our country tend to hold much water, and are characterized by good capillarity, which conditions facilitate the segregation of ice. The water content of the frozen soil of such types usually exceeds the saturation water content in the normal state. The samples of these types of freezing can not be produced in the ordinary container with artificial refrigeration, which was used by the former investigators for the conductivity test.

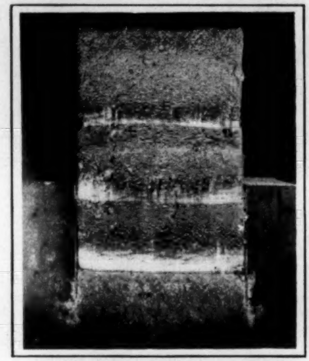

Fig. 1--A sample with remarkable frost heaving by the segregation of ice; soil C

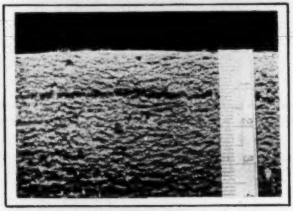

Fig. 3--Sirloin-type freezing; soil C, Experiment 95, r = 2.38, M = 0.31

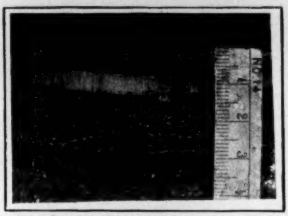

Fig. 2--Ice-filament layers; soil A; Experiment 68, r = 2.77, M = 0.26

Furthermore, for practical application, it is required to measure the conductivity of frozen soil under the condition that the direction of heat flow coincides with that of the natural state.

For these reasons, the author used a special vessel for the preparation of soil samples, and the measurement of conductivity was carried out with another apparatus. The soil samples of various modes of freezing were prepared by the artificial frost-heaving apparatus, and the diffusivity test was carried out by another apparatus designed for that purpose.

Principle and apparatus

New apparatus for the method of ANGSTROM [1861, 1864; GLAZEBROOK, 1950, p. 449]--The solution of the linear differential equation of the heat conduction

$$\partial u/\partial t = k\,\partial^2 u/\partial x^2 \quad \ldots\ldots\ldots (1)$$

is known to be

$$u = u_o \exp\left(-x\sqrt{\pi/kT}\right)\cdot\sin\left[(2\pi/T)t - x\sqrt{\pi/kT}\right] \quad (2)$$

when the boundary condition is

$$u_{x=o} = u_o \sin(2\pi/T)t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

T is the period of the temperature wave, and k is the thermal diffusivity of the sample.

One surface of the sample in parallelopiped form is heated, so that the boundary condition satisfies (3), and the temperature waves are measured at the two points x_1, x_2, distant from the surface, and the amplitudes A_1, A_2, and the phases ϵ_1, ϵ_2, are obtained. Then the thermal diffusivity k is given by the equation

$$k = \frac{\pi(x_1 - x_2)^2}{T(\log_e A_1/A_2)^2} = \frac{\pi(x_1 - x_2)^2}{T(\epsilon_1 - \epsilon_2)^2}$$

The thermal conductivity K of the soil is given as

$$K = c\rho k \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where c is the specific heat and ρ is the density of the sample.

For giving the boundary condition as shown by (3), an electric resistance has usually been used, which gives a sinusoidal form of heat generation in the heater. KING [1915] used a cam and TADOKORO [1921] designed a plectrum resistance for this purpose. In either of them, however, Table 1--The actual radii of the cam with respect to θ, b = 4.90 cm, a = 2.10 cm

θ	r	θ	r
° °	cm	° °	cm
0 or 180	7.00	180 or 360	7.00
10 or 170	7.18	190 or 350	6.81
20 or 160	7.33	200 or 340	6.58
30 or 150	7.47	210 or 330	6.39
40 or 140	7.59	220 or 320	6.15
50 or 130	7.69	230 or 310	5.90
60 or 120	7.77	240 or 300	5.67
70 or 110	7.83	250 or 290	5.41
80 or 100	7.86	260 or 280	5.16
90	7.87	270	4.90

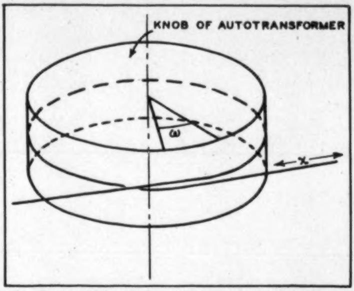

Fig. 4--Knob of the Slidac and string wound around it to change the rotation of the knob into linear motion

it must be noticed that the combined value $R = r + r'$ is effective in controlling the heating current i, where r is the variable series resistance inserted and r' is the resistance of heating coil. Therefore, the change of r' for various samples will give rise to the change of r, that is, the change of the design of the cam or of the plectrum resistance. This is the most inconvenient point of these methods. Furthermore, it is laborious and troublesome to build up the resistance r.

ISHIDA [1950] of our Laboratory, therefore, proposed a new method. The heat Q generated in the heating coil is expressed by

$$Q = V^2/R$$

The Slidac, a handy autotransformer for laboratory use, is used for varying the applied voltage V of the alternating current continuously, so that Q can be changed in sine form with respect to time.

It was verified that a linear relation holds with sufficient accuracy between the output voltage and the rotation angle ω of the knob of the autotransformer. Then the problem is solved if we rotate the knob in such a way that the square of ω is sinusoidal. Winding a string around the knob as shown in Figure 4, we can change the rotation of the knob into a linear motion, and vice versa. In order to make the square of the displacement of the string sinusoidal, a special cam was designed. For this purpose, we express the displacement x of the string by

$$x = a(1 + \sin\theta)^{0.5}$$

The form of the cam is given in polar coordinate as

$$r = b + x = b + a(1 + \sin\theta)^{0.5}$$

The form of the cam thus obtained is as shown in Figure 5, and its actual dimension is tabulated in Table 1.

The essential parts of the apparatus are shown in Figure 6. The cam C is driven by a motor, reducing its speed with two worm gears. The period is made to be about 35 minutes. The string S must be free from elongation or shrinkage. The Koto-string (Koto is the Japanese harp) is used for this purpose. It is wound around the knob K of the autotransformer L and fixed at a point on the knob. Passing through two pulleys P and Q, its one end is fastened to the end of a movable rod R. A spring is inserted in the cylinder A, which pushes this rod against the cam. The output voltage is varied between 0 and 22 volts for a complete rotation of the cam.

The heater and the specimen--The heater H consists of a coil of nichrome wire. It is buried in magnesia powder in a circular cylinder D. The soil specimen is 10 × 10 cm in dimension and 5 cm in height, packed in a wooden box B. In the case of the frozen soil, the specimen and the heater are set in a thermostat placed in the cold-chamber laboratory. The working temperature of this thermostat is about -20°C. Leading wires for the heater and the thermo-junctions are drawn out of the cold chamber, and the operation of the measurements are carried out in the ordinary room.

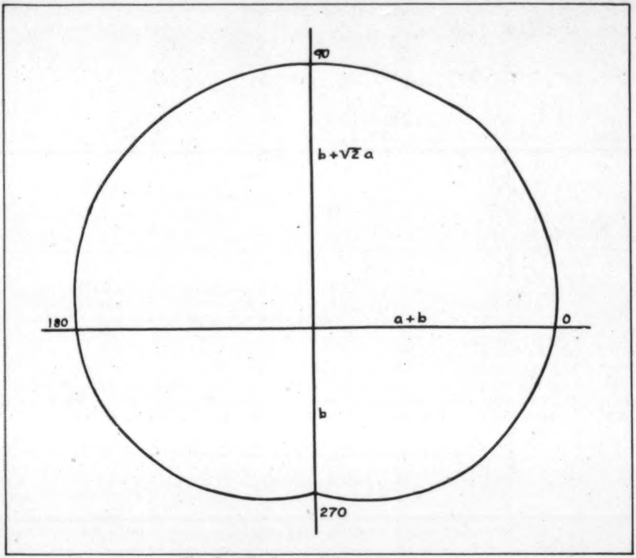

Fig. 5--The form of the cam

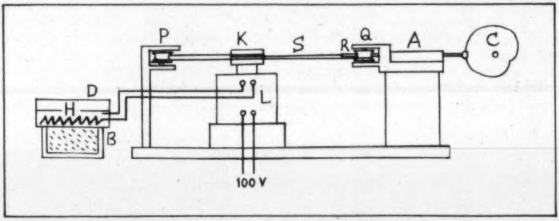

Fig. 6--Apparatus for the measurement of thermal diffusivity; C, cam; A, spring box; P, Q, pulleys; R, rod; S, string; K, knob; L, Slidac; H, heater; D, heater container; B, sample box

Preparation of the sample--Special precautions were paid to the preparation of the sample, so that it might be similar to that in nature.

The concrete-type freezing, that is, freezing of soil without marked segregation of ice, is obtained when the sample of smaller water content is made to freeze rather rapidly. As the sides and bottom of the wooden box container (10 × 10 cm in dimension and 4 cm in depth) are thermally insulated with a layer of sawdust, the moist soil sample in this container is cooled down only from the upper surface. When the container is placed overnight in the cold-chamber laboratory, the next morning we can have a sample of the concrete-type freezing.

The sirloin-type freezing and the ice-filament layer are produced in the artificial frost-heaving apparatus of an open system. The general view of the apparatus is shown in Figure 7. This is similar

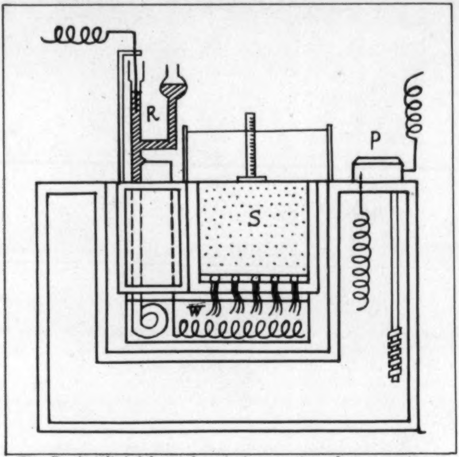

Fig. 7--Artificial frost-heaving apparatus of open system; S, soil sample; W, water; R, regulator for water temperature; P, regulator for container temperature

to the one which was originally designed by NAKAYA [1942]. The water is supplied through hanging cloth from the cistern placed below. The freezing proceeds from the upper surface. As the segregation of ice takes place in the soil sample, frost-heaving is observed.

By controlling the temperatures of the air and the water in the cistern, samples of various types of segregation of ice are produced. Some examples of these samples are shown in Figures 1, 2, and 3, among which Figures 1 and 2 show the ice-filament layers, and Figure 3 the sirloin-type freezing. As a test specimen, a block of about 10 × 10 × 4 cm in size is cut from the sample thus produced.

Experimental procedure

The temperature waves were measured at two points about one centimeter apart along the center line of the specimen by two hair thermo-junctions of copper constantan. For this purpose, two fine holes were drilled from a side. They are seen as two black dots in Figures 2 and 3. The temperature could be measured with an accuracy of 0.01°C with a short-period galvanometer. The temperature measurements were carried out every minute, and the values were plotted against time.

Adjusting both the power supply to the heater and the temperature of the thermostat, the mean temperature between two thermo-junctions in the specimen was maintained at a required value. The measurements were made for the wet soil at room temperature and for the frozen soil in the cold chamber, the mean temperature having been adjusted about 30°C for the former and at about -5°C for the latter. The amplitude of the temperature wave at the upper thermo-junction was kept within a range of about 2°C.

One example of the measurements of the temperature waves is shown in Figure 8. The ordinate is the reading of the galvanometer scale, and the abscissa is the time. Each temperature-time curve shows a perfect sinusoidal form. The period T and the phase difference $\epsilon_1 - \epsilon_2$ were measured from wave trains.

We calculated the thermal diffusivity from the phase difference by (4). Considering the variations in the amplitudes of the waves caused by some unavoidable fluctuation in the input voltage, the calculation of diffusivity from phase difference seems to be better than that from the amplitudes ratio.

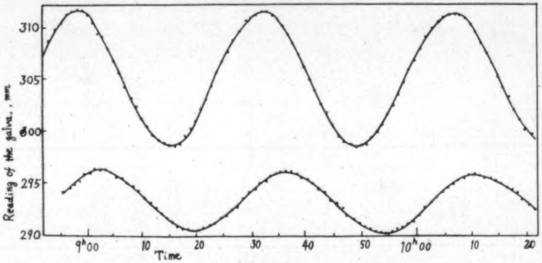

Fig. 8--An example of the temperature time curves, Experiment 15

In order to compute the thermal conductivity from the diffusivity thus obtained, it is necessary to know the volume specific heat of soil, which can be calculated from the specific heat of dry soil, that of water for the wet soil, and of ice for the frozen one. The specific heat of dry soil was measured by the method of mixture using an ordinary calorimeter. As for the frozen soil, it was measured at -5°C, using alcohol cooled below -30°C as working liquid in the calorimeter.

Specific gravity of the soil material was measured by a pycnometer. Mechanical analysis of the soil was carried out by the method of hydrostatic sedimentation. Saturation moisture ratio was determined by the ordinary gravimetric method. The saturation was obtained by absorbing water from below by the capillary action of the soil.

Results of the experiments

Three volcanogenous soils were tested, which were taken at Memuro in Hokkaido. These three soil samples are designated as A, B, and C for convenience. Results of the mechanical analysis of these three soil samples and the other physical constants are tabulated in Table 2.

Table 2--General physical properties of sample soils

Soil	Nature of soil	Depth from ground surface	Mechanical analysis			Specific weight	Thermal capacity of dry soil		Saturation moisture ratio at close packing
			Sand >0.05 mm	Silt 0.05-0.005 mm	Clay <0.005 mm		30°C	-5°C	
		cm	pct	pct	pct	gm/cm^3	cal/gm°C		
A	Black cultivated soil	0-10	61.7	18.5	19.8	2.43	0.21	0.17	0.6
B	Brown subsoil	25-30	72.8	20.6	6.6	2.56	0.26	0.19	0.7
C	Yellow brown subsoil	50-60	52.8	30.2	17.0	2.59	0.26	0.19	0.6

Thermal conductivity of wet soil at room temperature and its relation to the moisture ratio--The thermal diffusivity k' of soil B was measured at room temperature as the function of moisture ratio r. The results of the experiments are tabulated in Table 3 as an example of wet soil of close packing. In this Table, the moisture ratio r means the ratio of the mass of water to that of dry soil, and the dry density M is the mass of the dry soil in unit volume of the sample. The results are shown in Figure 9 with open dots.

Thermal conductivity K' is given by $K' = c\rho k'$, where $c\rho$ is the volume specific heat of soil sample. Neglecting the specific heat of air void, it is represented as

$$c\rho = sM + irM \quad \ldots\ldots\ldots\ldots \quad (6)$$

Table 3--Results of the measurements of the thermal diffusivity of soil B, close packing

Experiment	$k' \times 10^3$	$x_1 - x_2$	$\epsilon_1 - \epsilon_2$	r	M
	cgs[a]	cm			gm/cm^3
10	1.83	0.72	0.656	0.21	0.71
11	2.48	1.07	0.837	0.53	0.66
12	2.06	1.21	1.037	0.84	0.69
14	1.31	0.93	1.000	0.00	0.90
15	1.95	1.91	0.803	0.93	0.73
16	2.41	0.85	0.674	0.52	0.64
17	1.87	0.76	0.685	0.40	0.64

[a] The cgs unit of thermal diffusivity is cm^2/sec, and that of thermal conductivity is cal/cm sec deg C.

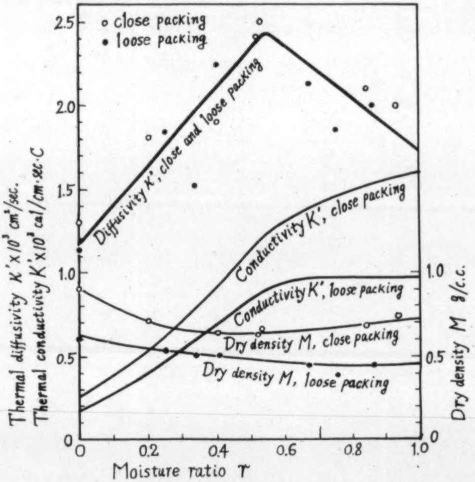

Fig. 9--Relations between the moisture ratio of wet soil and its thermal diffusivity or conductivity, measured at room temperature

where M is the dry density, r the moisture ratio, s the specific heat of dry soil, and i the specific heat of water. In the case of the frozen soil, i is the specific heat of ice. The values of s for three samples of soils measured at 30° C and -5° C respectively are shown in Table 2, and i is taken as 0.999 cal/gm deg C at 30°C and 0.485 cal/gm deg C at -5°C.

When the samples are produced in the state of close packing, M varies with r. The values of M are picked up from Table 3 and plotted against r in Figure 9 with the open dots. Because of the difficulty for getting constant degree of packing, the dots are rather scattered. The curves are drawn by drawing a smooth curve based on the points. Values of M are read for every 0.1 of r, and the values of $c\rho$ are calculated for every 0.1 of r using the values of M thus obtained. They are tabulated in the left part of Table 4.

Table 4--Calculation of the volume specific heat and the thermal conductivity of wet soil B at room temperature

r	M	$c\rho$	$k' \times 10^3$	$K' \times 10^3$
	gm/cm^3		cgs	cgs
0.0	0.90	0.23	1.15	0.27
0.1	0.78	0.28	1.39	0.39
0.2	0.71	0.33	1.63	0.53
0.3	0.66	0.37	1.86	0.69
0.4	0.64	0.42	2.11	0.89
0.5	0.64	0.49	2.34	1.14
0.6	0.64	0.55	2.37	1.30
0.7	0.66	0.63	2.20	1.39
0.8	0.68	0.72	2.06	1.49
0.9	0.70	0.81	1.88	1.53
1.0	0.72	0.91	1.75	1.59

Similarly the values of k' are read on Figure 9, and K' is computed by $K' = c\rho k'$ for every 0.1 of r. Results of these calculations are tabulated in the right half of Table 4, together with the value of k'. From Table 4, we get the curve of K' as a function of r, also shown in Figure 9.

Similar experiments were carried out in the state of loose packing, using the same soil B. The results are shown in Figure 9 with solid dots. Summarizing the results, we note that the thermal diffusivity appears to be independent of the degree of packing and shows a maximum value at a certain value of moisture ratio, the value being nearly 0.5 in the case of soil B. Similar curves were obtained for soils A and C. The value of r giving the maximum diffusivity is about 0.2 for soil A and 0.4 for soil C respectively. The results are shown in Figure 10.

Returning to Figure 9, the thermal conductivity shows a quite different mode from the thermal diffusivity. It is a function of the degree of packing and shows a higher value for the close packing than for the loose packing. The maximum is not observed in K'-curve, but seems to approach a certain value for the larger values of r.

Thermal conductivity of frozen soil in the region below saturation water content--The measurement of the thermal diffusivity of frozen soil was carried out in the cold chamber. The thermal diffusivity K of frozen soil as the function of its moisture ratio r is tabulated in Table 5.

These results are shown graphically in Figure 10. The open dots represent the thermal diffusivity k in the frozen state (see Table 5). The line is drawn by smoothing these white dots. In the region of the water content below saturation, these values of k are expressed by an empirical formula of the form

$$k = ae^{br}$$

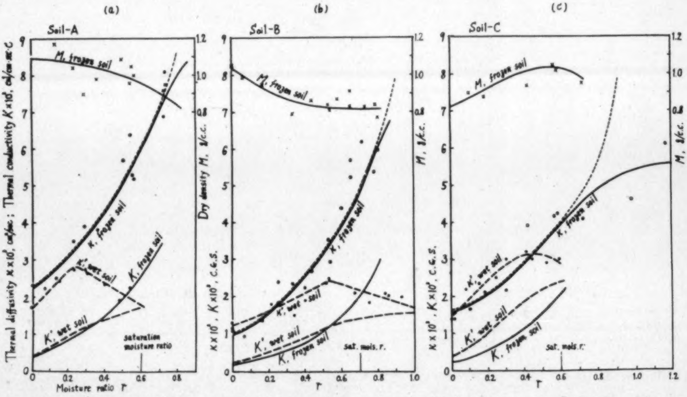

Fig. 10--Relations between the moisture ratio and thermal diffusivity or conductivity of frozen soil and those of wet soil for various soil samples

Table 5--Thermal diffusivity of frozen soils at -5° C

Soil	Experiment	r	$k \times 10^3$	M	Soil	Experiment	r	$k \times 10^3$	M
			cgs	gm/cm^3				cgs	gm/cm^3
A	51	0.50	5.69	1.09	B	76	0.65	5.67	0.83
	52	0.38	2.68	0.94		77	0.68	6.21	. . .
	53	0.29	3.92	0.90		78	0.65	5.27	0.91
	54	0.56	5.17	1.00		80	0.16	1.37	0.94
	55	0.55	5.31	1.05		82	0.53	3.56	0.84
	56	0.23	3.48	1.04		83	0.73	5.37	0.83
	57	0.54	6.38	0.96		84	0.06	0.95	0.99
	58	0.00	2.28	1.10		86	0.01	1.12	1.05
	61	0.36	3.78	0.98					
	62	0.13	2.46	1.17	C	101	0.72	4.13	0.90
						102	0.30	2.17	. . .
B	71	0.25	2.38	. . .		103	0.58	4.25	1.02
	72	0.34	2.32	0.79		104	0.10	1.65	0.90
	73	0.44	2.66	0.86		105	0.18	2.14	0.88
	74	0.54	2.95	0.81		106	0.56	4.16	1.05
	75	0.58	4.36	0.86		108	0.42	3.90	1.04

where a and b are constants. The numerical values of these constants for the dotted lines drawn in Figure 10 are tabulated in the left part of Table 6. In Figure 10 we see that the dotted line coincides with the full line below saturation.

Table 6--Numerical values of constants for the empirical formulas $k = ae^{br}$ and $K = ce^{dr}$

Soil	Thermal diffusivity		Thermal conductivity	
	$a \times 10^3$	b	$c \times 10^4$	d
	cgs		cgs	
A	2.25	1.62	4.81	2.84
B	1.00	2.23	2.12	3.29
C	1.57	1.56	2.68	3.46

The solid dots in Figure 10 represent the thermal diffusivity k′ of the soils at room temperature. They were obtained for soils A and C by the similar experiment as for soil B described above. The broken lines in Figure 10 are obtained by smoothing the values of black dots. They show the relationship between the thermal diffusivity k′ and the moisture ratio r. The curve for soil B is reproduced from Figure 9. K′-curves, shown in Figure 10 with broken lines, were calculated from the value of k′ as described above.

Thermal conductivity K of frozen soil is computed in similar manner as the case of K′. In this case i in (6) is taken as 0.485 cal/gm deg C as it is the specific heat of ice at -5° C. The M-curves are drawn by smoothing the cross marks which were plotted from Table 5.

Values of M and calculated values of $c\rho$ are tabulated in the left part of Table 7 for every 0.1 of r. The calculated values of K for the frozen soil are shown in the right part of Table 7. Relations between K and r are also shown by full lines in Figure 10.

These K-curves for frozen soils are expressed by an empirical formula of similar form as the case of k-curves

$$K = ce^{dr}$$

where c and d are constants. The numerical values of these constants for the three soils are tabulated in the right part of Table 6. This form of the empirical formula also holds only in the region below the saturation moisture ratio.

KERSTEN [1949] proposes an empirical formula of the form K = A + Br for the thermal conductivity of frozen soils. His formula seems to be the first approximation of our formula, and for

Table 7--Calculation of the volume specific heat and the thermal conductivity of frozen soils

Soil	r	M	$c\rho$	$k \times 10^3$	$K \times 10^3$
		gm/cm^3	cal/cm^3	cgs	cgs
A	0.0	1.09	0.185	2.25	0.42
	0.1	1.08	0.235	2.60	0.61
	0.2	1.07	0.285	3.10	0.83
	0.3	1.05	0.331	3.65	1.21
	0.4	1.03	0.374	4.30	1.61
	0.5	1.00	0.411	5.05	2.08
	0.6	0.96	0.444	6.10	2.71
	0.7	0.90	0.467	7.30	3.40
B	0.0	1.04	0.198	1.00	0.20
	0.1	0.96	0.228	1.25	0.29
	0.2	0.91	0.261	1.60	0.42
	0.3	0.87	0.291	2.05	0.60
	0.4	0.85	0.325	2.60	0.85
	0.5	0.84	0.362	3.20	1.16
	0.6	0.83	0.398	4.00	1.59
	0.7	0.825	0.435	5.15	2.24
	0.8	0.82	0.464	6.20	2.88
C	0.0	0.80	0.152	1.60	0.25
	0.1	0.87	0.207	1.80	0.37
	0.2	0.93	0.267	2.10	0.55
	0.3	0.98	0.328	2.40	0.80
	0.4	1.02	0.391	2.95	1.15
	0.5	1.03	0.444	3.55	1.58
	0.6	1.02	0.489	4.00	1.96

the smaller values of r these two equations come to the same expression. The exponential relation will be the general form between K and r for frozen soils.

Thermal conductivity of frozen soil in the region above saturation water content--Because of the segregation of ice, the samples of sirloin-type freezing and ice-filament layer types usually contain water in excess of the saturation water content. Measurements of k and K were also carried out for these. The results are tabulated in Table 8. From these results we see that the diffusivity in the region above saturation water content also increases with the moisture ratio, but the rate of increase is smaller than the case below saturation. These results are also shown in Figure 10. It is clearly seen that k-curves in this region have smaller values than the exponential curves, which hold well for the region below saturation. For far larger values of r, the thermal diffusivity

Table 8--Thermal diffusivity of frozen soils with the segregation of ice

Soil	Experiment	Type of freezing	r	$k \times 10^3$	M
				cgs	gm/cm^3
A	59	Sirloin type	0.72	6.88	0.91
	63	Sirloin type	0.73	8.12	0.85
	64	Sirloin type	2.13	9.40	0.38
	68	Ice-filament layer	2.77	8.30	0.26
B	79	Sirloin type	0.79	5.39	0.84
	85	Sirloin type	0.80	6.02	0.77
C	91	Sirloin type	1.33	7.47	0.82
	93	Sirloin type	1.84	6.73	0.41
	95	Sirloin type	2.38	6.04	0.31
	97	Sirloin type	1.17	6.09	0.63
	107	Sirloin type	1.08	4.62	0.66

of these frozen soils will approach the value of ice, that is, 0.011 cgs.

Variation of the thermal diffusivity due to the direction of heat flow--When the ground is cooled gradually from the surface and sufficient water is supplied from the soil below, ice layers are segregated from the soil. In nature, these ice layers lie in a position perpendicular to the direction of heat flow.

Those frozen soils with segregated ice layers may have different thermal properties for different directions. If any difference exists, it would appear markedly in the case of the sirloin-type freezing. All the measurements described above are for the case in which the direction of heat flow is parallel to the direction of freezing. This case is expressed by the symbol ||. The thermal diffusivity is measured also for the same specimens in the case when the directions are perpendicular with each other. The value is marked with ⊥.

The drilling of the holes for the thermo-junctions were made carefully, so that the measurement could be taken in the neighborhood in both cases. The section views of the sample used in this experiment are shown in Figure 11. Figure 11 (a) is the parallel case ||, and (b) is the case when the specimen is rotated by right angle around the horizontal axis, that is, ⊥. In both cases, the direction of heat flow for measuring the thermal diffusivity is from top to bottom in the photograph. The results obtained for various values of moisture ratio are tabulated in Table 9. In three of five tests, the parallel values are the greater, and in two, the perpendicular. No simple relation is observed with moisture ratio. At present we are led to the conclusion that the difference of the thermal diffusivity for different directions of heat flow is small and complicated so that no simple relation is observed. It is assured that the effect of the direction of heat flow can be neglected for the practical application.

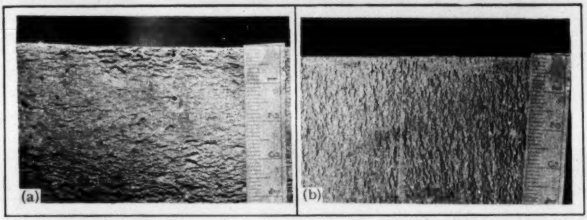

Fig. 11--Section view of the sample used in the experiment to test the variation of the thermal diffusivity of the frozen soil in relation to the direction of heat flow; (a) Exp. 97 ||; (b) 98⊥; $r = 1.17$, $M = 0.63$; the direction of heat flow for measuring the thermal diffusivity is from top to bottom in this photograph

Table 9--Variation of the thermal diffusivity due to the direction of heat flow

Soil	Experiment	r	$k \times 10^3$	
			||	⊥
			cgs	cgs
A	64, 65	2.14	9.4	8.1
C	91, 92	1.33	7.5	6.4
	93, 94	1.84	6.7	8.2
	95, 96	2.38	6.0	5.6
	97, 98	1.17	6.1	6.5

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SEA-WATER INTRUSION IN COASTAL AQUIFERS

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Abstract--This paper describes briefly the sea-water intrusion problem in California, methods of control, certain fundamentals of sea-water intrusion, and applicability of electrolytic model studies. An example of intrusion in Salinas Valley is presented.

Introduction--The problem of sea water penetrating inland through ground-water aquifers is one which has received frequent mention in the literature for the past 100 years. From one of the earliest studies of this problem in England by BRAITHWAITE [1855] describing increasing salinity of water pumped from wells in London and Liverpool to the present-day problem of sea-water intrusion along the California coast, the subject has been of considerable interest. Today sea-water intrusion is receiving significant attention in California because of the economic importance of the phenomenon in contaminating coastal water supplies. According to information collected by the Division of Water Resources of the State of California [BANKS, GLEASON, and RICHTER, 1950], over 90,000 acres of coastal lands have been contaminated by sea-water intrusion. These penetrations have occurred in 13 distinct areas along the coast, and there is further danger in numerous other areas in the future. Most of these intrusions are in confined (pressure) aquifers, caused by heavy pumping drafts from concentrated irrigation and population demands. Before California coastal areas were developed to their present stage, most of these now-critical areas produced flowing wells of fresh water. These gave early water users the impression that unlimited supplies of water were available in the ground. In a short time, however, wells ceased to flow and pumping became standard procedure. Well concentrations soon increased to such an extent that more water was being pumped from than recharged into the ground. The result was increased pumping lifts. This changed the normal fluid potential distribution with fresh water flowing seaward, and allowed sea water to enter aquifers which had been occupied by fresh water. To combat this problem extensive investigations are under way by the Los Angeles County Flood Control District [LAVERTY, 1952], the State of California [BANKS and BOOKMAN, 1951], and the University of California [ANONYMOUS, 1951].

Five methods have been proposed to control intrusion [BANKS and BOOKMAN, 1951]: (a) raising of ground-water levels above sea level by reduction or rearrangement of pumping draft patterns; (b) direct recharge of overdrawn aquifers to maintain ground-water levels at or above sea level; (c) development of a pumping trough adjacent to the coast; (d) maintenance of a fresh-water ridge above sea level along the coast by injection wells; and (e) construction of artificial subsurface dikes.

Of these, the latter two appear to be the most feasible from economic and practical standpoints. Cutoff walls containing bentonitic clays, cement grout, asphalt emulsions, or other compounds can be constructed to depths of 200 ft. In certain areas this will be sufficient to limit sea-water penetration. In deeper and confined aquifers, injection wells may be useful to reverse the landward flow of sea water, although they are only a temporary expediency. Such wells might serve to build and to maintain pressure ridges paralleling the coast which would distribute fresh water both landward and seaward.

The purpose of this paper is to review very briefly some of the fundamentals involved in sea-water intrusion, since many of them come from other fields of study, and to describe one instance of intrusion where sufficient data are available. Current field and laboratory research may be expected to contribute materially to our knowledge of this increasingly important problem.

Interface depths--More than 50 years ago BADON GHYBEN [1889] in Holland and HERZBERG [1901] in the East Frisian Islands off the coast of Germany found that the depth to salt water was a simple function of the height of the water table above sea level and of the densities of the fresh and salt water. This relationship may be expressed as

$$Z_{23} = [\rho_f/(\rho_s - \rho_f)]\, Z_{12} \quad \ldots\ldots (1)$$

where Z_{23} is the depth to the interface between fresh water and salt water below sea level, Z_{12} is the height of the fresh water above sea level, ρ_f is the density of fresh water, and ρ_s is that of salt water. This expression is derived directly from an assumption of hydrostatic equilibrium in which a column of salt water balances a column of fresh and salt water. Depending upon the density values used, (1) indicates that Z_{23} is from 37 to 40 times greater than Z_{12} [WENTWORTH, 1939]. Since the original studies, others have appeared based on observations of coastal wells, which have been in agreement with the Ghyben-Herzberg principle. These studies have included further work in Holland by PENNINK [1905], in Belgium by D'ANDRIMONT [1902], and more recently in Florida by BROWN and PARKER [1945], and in the Marianas Islands by OHRT [1947]. It is manifest that sea water does not exist everywhere under continental areas, so that the extent and continuity of the primary aquifers impose a natural boundary upon the application of the principle [BROWN, 1925; NOMITSU, TOYOHARA, and KAMIMOTO, 1927].

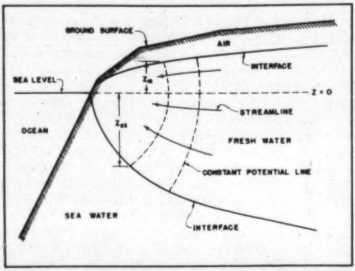

Fig. 1--Schematic diagram showing interfaces between fresh water and air, and between fresh and salt water in an unconfined coastal aquifer

In recent years it has been recognized that the Ghyben-Herzberg principle is really a great simplification of the actual ground-water picture [KRUL and LIEFRINCK, 1946]. HUBBERT [1940] clearly showed that the principle is valid only for hydrostatic equilibrium and that this assumption is not correct for ground-water flow conditions. If it were, horizontal interfaces would result with fresh water everywhere floating above salt water. Thus, as shown in Figure 1, the differences in elevation from sea level are measured to points of intersection of a constant fluid potential line (in the two-dimensional case) with the two interfaces. These two points will lie on a single vertical line only if the fresh water is flowing uniformly and horizontally or if the fresh water is static. Since neither of these situations occur in the field, the points will not lie on a vertical line. Thus theoretically at any given point the depth of fresh water above sea level is not simply related to the fresh-water depth below sea level at the same point.

The question naturally arises as to why the Ghyben-Herzberg principle has been verified from actual measurements. To answer this, attention should be directed to modifications which affect field measurements of interface depths. Sympathetic tidal fluctuations in coastal aquifers [BROWN, 1925; ISAACS and BASCOM, 1949] continuously shift the fresh-water interface. Diffusion introduces the problem of density changes. In beach zones this effect may be of sufficient magnitude to introduce discrepancies in identification of interfaces [TOYOHARA, 1935] or to obscure completely the interface between fresh and salt water (lower interface). Nevertheless, most observations have confirmed the Ghyben-Herzberg relationship. Under conditions of low potential gradients, hydrostatic equilibrium may be assumed as a first approximation, and the computed depths will check observed depths when allowance is made for inaccuracies of measurement. Where steep potential gradients frequently occur, however, as near pumping wells, canals, rivers, and coastal areas, large errors may be incurred.

Interface slopes--Expressions for the slopes of interfaces were derived by HUBBERT [1940] in terms of fluid potential gradients. By application of Darcy's law these may be expressed in terms of the flow conditions. From

$$\partial\phi/\partial s = -q/\sigma \quad \ldots\ldots (2)$$

where $\partial\phi/\partial s$ is the potential gradient, q is the discharge per unit area, and σ is the combined permeability parameter [HUBBERT, 1946], the slopes become

$$\left.\begin{aligned} \sin\alpha_{12} &= -(1/g)\, q_f/\sigma_f \\ \sin\alpha_{23} &= (1/g)\,[\rho_f/(\rho_s - \rho_f)]\, q_f/\sigma_f \end{aligned}\right\} \quad \ldots\ldots (3)$$

The sine functions measure the angle of the interfaces from the horizontal in the direction of fresh water flow. Equations (3) show that the slopes are directly proportional to the magnitude of the fresh-water flow q_f, and that the fresh-water interface tilts downward in the direction of fresh-water flow, while the fresh lower interface tilts upward in the same direction. Thus the cross-sectional area available to fresh-water flow will become progressively smaller, causing q_f to increase proportionately. As a result, the interfaces will be concave toward the fresh water, as illustrated in Figure 1.

Capillarity--The effect of capillarity is of course negligible on the lower interface, but it does have an effect on the interface between the fresh water and the air (upper interface). Detailed investigations by RICHARDS [1931] and LEVERETT [1940], among others, have shown the dependency of capillary pressure upon the interfacial tension and curvature of the fluid. SMITH [1933] studied the phenomenon in uniform spheres, and more recently LAMBE [1951] investigated capillarity in sands. Investigations by MAVIS and TSUI [1939] and HUBBERT [1940] have been concerned with flow conditions above the "water table" as observed in a well.

Trans-interface flow--Interfaces are generally treated as fluid boundaries. At actual ground-water interfaces, however, processes occur which introduce passage of fluids across the interface. The most important of these are percolation and evaporation across the upper interface and diffusion across the lower interface.

Water percolating downward from the ground surface flows through partially saturated pores until reaching the fresh-water (upper) interface. Here it combines with the fresh-water flow in completely saturated pores. JACOB [1950] has pointed out that this process causes ground-water streamlines to form very flat angles with the interface. This added water raises the interface in proportion to the volume of surcharge, as is commonly observed after periods of above-average rainfall. The intensity and duration of rainfall, surface infiltration, stratigraphy, and permeability of the overburden determine the amount of water joining the ground-water flow. In beach areas noticeable changes in salinity may occur in connection with the dilution provided by percolating water [BROWN, 1925].

Evaporation from the upper interface has the opposite effect to that of percolation, but the quantity of water transferred is ordinarily considerably smaller. Neglecting the minor role of water quality, evaporation from ground water depends upon the temperature of the ground water and upon the vapor-pressure differential across the interface. Because of the usual uniformity of ground-water temperatures, the vapor-pressure differential in a constant-temperature region (geothermal gradients are insignificant over the short distances here considered) becomes the controlling factor [BAVER, 1948]. This in turn is influenced by the degree of saturation above the interface and by the relative permeability of the medium to vapor. It is safe to assume that evaporation from interfaces located below the zone of surface modifications is slight. On the other hand, as the interface approaches the ground surface, evaporation may become significant. Here convective air movement induced by radiational heating of the upper soil layers can develop sizeable vapor-pressure gradients and large amounts of water can evaporate. PARSHALL [1930] showed this to be true from soil-evaporation experiments.

Diffusion, here defined as the intermingling of fresh and salt waters at their interface resulting from molecular dispersion between the two fluids, is an instance of a fluid interface not serving as a complete boundary. The rate of diffusion between two fluids in a vertical column of uniform cross-section is proportional to the concentration gradient [GLASSTONE, 1946; LONGSWORTH and Others, 1945]. Thus fresh water and salt water initially in contact show relatively high diffusion rates, which become progressively smaller as the diffusion zone increases and the concentration gradient decreases. Laboratory experiments in this connection have indicated the effect of diffusion to be small [D'ANDRIMONT, 1905; NOMITSU, TOYOHARA, and KAMIMOTO, 1927]. Because diffusion rates are smaller than usual ground-water velocities, the diffusion zone is limited to a narrow band. Field measurements of diffusion zones by BROWN [1925] and SWARTZ [1937] have confirmed this.

Base exchange--Of several types of changes in chemical composition which sea water may undergo as it enters and moves through coastal aquifers [REVELLE, 1941], base-exchange activity is believed to be the primary cause of chlorinity gradients found in sea-water intrusion zones [LOVE, 1944]. Because of changes in composition, the presence of sea water in ground-water aquifers is not always apparent. A criterion for recognition of sea water, consisting of the weight ratio of chloride to bicarbonate, was introduced by REVELLE [1941]. SIMPSON [1946] applied this criterion in the form of a linear relation between the chloride-bicarbonate ratio and total anions for detection of intrusion in the Salinas Valley of California.

Confined aquifers--Most intrusion areas along the California coast involve confined aquifers [TODD, 1952]. Relatively impermeable overlying clay layers commonly identify these aquifers. In such zones the fluid potential distribution is independent of that in the overlying unconfined aquifers. Pressure existing in the aquifer may be thought of as being balanced by two components: (1) atmospheric pressure, and (2) weight of the overlying soil burden not supported by the porous media within the aquifer. Equations for flow in confined aquifers taking into account the elasticity of confined aquifers and the compressibility of water have been derived by JACOB [1940] and WERNER [1946].

In addition to intrusion resulting from deficiencies of fresh water in a confined aquifer, sea water may also cause contamination by entrance through natural or artificial breaks in the overlying clay layers. Lowering of artesian pressures by excessive pumping may permit saline water to enter an aquifer from upper unconfined zones through leaky casings of old, abandoned, or improperly sealed wells. Much of the intrusion problem in Santa Clara County, California, has been traced to this method [BANKS, GLEASON, and RICHTER, 1950]. Similar damage can result from improperly constructed gravel-packed wells in which the gravel packing extends beyond the aquifer being pumped and serves as a channel for admitting undesirable water [BANKS and LAWRENCE, 1953].

Electrolytic models--The effect of injecting fresh water through a system of wells to limit sea-water intrusion, as already mentioned, can be studied advantageously by means of electrolytic models. Analytical treatments of such systems may become quite complex, whereas a model reveals directly the flow patterns and interfacial positions of the injected water. Important contributions to electrolytic model design, development, and application have been made in the petroleum industry where similar problems have arisen in connection with water flooding and gas cycling operations [WYCKOFF, BOTSET, and MUSKAT, 1933; HORNER and BRUCE, 1944; BOTSET, 1946]. This type of model is particularly suited to multiple-well systems [MUSKAT, 1937]. Based on the analogy of Darcy's law and Ohm's law, the lines of current flow and constant potential in an electrical system may be made to simulate streamlines and lines of constant fluid potential in an aquifer. The movement of water from injection wells can be duplicated by employing an electrolyte containing an ion indicator which changes color with travel of the ions from the input electrode. Successive photographs of the model furnish a complete record of the movement which corresponds to that of injected water.

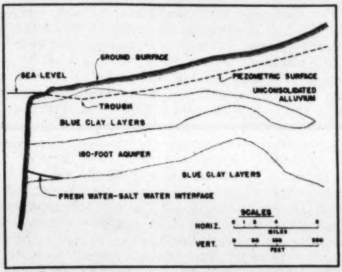

Fig. 2--Longitudinal cross-section of Salinas Valley, California, showing sea-water intrusion into confined 180-ft aquifer as of August, 1945

Intrusion in the Salinas Valley, California--An interesting example of sea-water intrusion into a confined aquifer is that of the Salinas Valley, California (Fig. 2). The principal confined aquifer, known as the 180-ft aquifer because of its average depth below ground surface, extends 28 miles inland from Monterey Bay, averages 4 1/2 miles in width, and has an average thickness of about 100 ft. Extensive blue-clay layers bound the aquifer vertically. A deep ocean canyon exists a short distance from the coast so that sea water is easily accessible to the valley aquifers. From a detailed study of this valley by SIMPSON [1946] the extent of penetration into the 180-ft aquifer was determined. This is based upon the extensive series of well logs and water-level measurements available. The piezometric surface, as indicated in Figure 2, forms a trough paralleling the coast at this time of year resulting from intensive pumping for irrigational needs. SIMPSON [1946] found that this trough is a seasonal phenomenon, appearing in the summer and disappearing in late fall as pumping decreases. This introduces oscillatory movements of sea water into and out of the aquifer annually. Salinity measurement in wells revealed that sea water had advanced 1 1/2 miles inland in 1945 and had polluted an area of some 6000 acres. The rate of encroachment was 600 ft/yr from 1944 to 1945 and it has continued at a variable rate since that time.

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SEISMIC AND GRAVITY INVESTIGATIONS ON THE MALASPINA GLACIER, ALASKA

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(Contribution No. 617, Division of the Geological Sciences, California Institute of Technology, Pasadena, California)

Abstract--Seismic reflections obtained from bedrock beneath the Malaspina Glacier along a ten-mile profile line indicate ice thicknesses ranging from 1130 to 2050 ft. The base of the ice is 700 ft below sea level near the center of the profile and shallows both northward toward the mountains and southward toward the ice margin. Good reflections were obtained with dynamite charges of about one ounce in 26-ft water-filled shot holes but only in relatively crevasse-free areas. Deeper reflections substantiate the inferred sedimentary nature of the subglacial rocks and show geologic structures consistent with the regional pattern. Gravity measurements along the central three miles of the seismic profile line indicate a gentle northwest-southeast trending subglacial topographic grain. Seismic refraction shots beyond the present margin of the glacier suggest a thickness of unconsolidated proglacial deposits in excess of 500 ft.

Introduction

During July and August, 1951, seismic and gravity investigations were carried out on the Malaspina Glacier of southeastern Alaska (Fig. 1) for the purpose of determining ice thickness and configuration of the subglacial floor. Although of interest in itself, the geophysical information was obtained primarily to aid in the investigation of structural relationships and modes of flow within this glacier. The Malaspina, a fan-shaped sheet of ice covering more than 1000 sq mi, is the type example of a piedmont glacier as defined by [RUSSELL [1891]. Its present regime is one of rapid deterioration [SHARP, 1951]. Twenty-seven days were devoted to seismic studies and ten days to gravity measurements.

Seismic reflection shooting

General statement--Seismic reflections were obtained along a ten-mile north-south profile line passing through Glacier Camp and aligned approximately parallel to the assumed direction of ice flow inferred from structures in the ice (Fig. 1). The usual interval between shooting stations along this line was 5000 ft. The nature of the ice-bedrock interface beneath the glacier can only be surmised, but the regional geology [RUSSELL, 1892; TARR and BUTLER, 1909; MILLER, 1951] suggests that early Tertiary clastic sedimentary rocks of the Yakataga and Poul Creek formations lie beneath the ice. Reflections from several deep horizons tend to substantiate the sedimentary nature of the subglacial rocks. The reflection coefficient of an interface between ice and sedimentary rock might conceivably be small (high velocity, low density versus high density, low velocity), but in this area a good reflection coefficient in the order of 0.4 is suggested by the high degree of consolidation of the Yakataga series where exposed 30 miles to the west.

Seismic procedure--A century six-trace portable seismic outfit was used. It was mounted on a toboggan sled which could be hauled by two men over smooth ice, but three men were required in moderately crevassed areas. Moving the seismic equipment from station to station usually required more time than the actual setting-up and shooting operation. Use was made of the project's helicopter on several occasions, but poor weather and limited gasoline restricted its operation more than anticipated.

The following conditions were required for the recording of recognizable reflections:

(1) Crustal conditions--Except in the earliest phases of the operation, snow from the previous winter was absent from the glacier's surface, so for the most part geophones were placed directly on glacier ice and all shot holes bottomed in ice, not in snow or firn. The best records were obtained from areas in which the ice was relatively thin, with all the openings seemingly filled with water, and the surface smooth. Poor results were obtained in crevassed areas in which the ice was riven with fractures and lacking water even in deep openings. The foliation and sizes of crystals seemed to have no effect. Along the seismic profile line, the ice was essentially free of debris except for local accumulations of surficial silt.

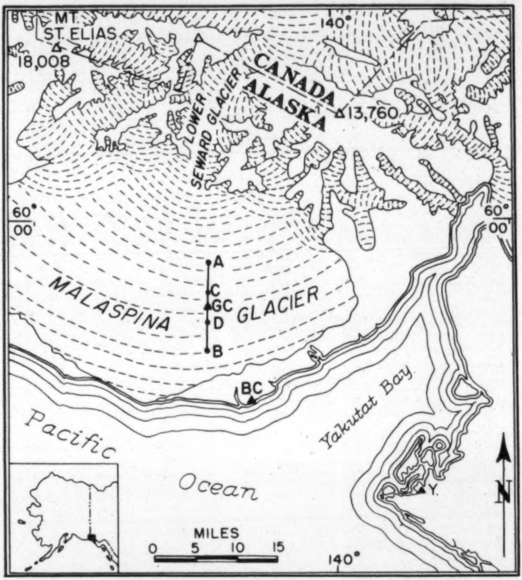


Fig. 1--Map of Malaspina Glacier and vicinity; Y, Yakutat Village; BC, Beach Camp; GC, Glacier Camp; A-B, seismic profile line; C-D, gravimeter profile line

(2) Size and placement of the explosive charge--The procedure finally developed was to place a charge of about one ounce of 60 pct high-velocity gelatin, tamped with water, in a 1 1/2-inch hole drilled to a depth of 26 ft.

As a result of the interest expressed by many persons in the problems of mechanical drilling in glacier ice, a drawing of the ice drill used in making shot holes is included (Fig. 2). This drill, modified from AHLMANN [1935] after Koch and Wegener, was the most satisfactory of several experimental models. Drilling was in coarsely crystalline ice, not firn. If the drill point was correctly sharpened, about 100 turns were needed to fill the drill barrel, and approximately 30 fillings were needed to make a 26-ft hole (the total length of the drill plus seven extensions). The time necessary for each drill hole was approximately two hours. This includes the drilling time as well as that required to remove and empty the drill barrel every load.

No satisfactory reflections were obtained from charges less than 20 ft deep in spite of numerous attempts. Experimentation was simple because the holes did not deteriorate with repeated shooting. The following techniques were also unsuccessful: charges in crevasses or water-filled moulins even though at considerable depth, charges without water tamping, use of a cap alone, dropping a sledge or hammering on the surface, or shooting single charges of various sizes in the air. No geometric patterns of air charges were set off, as recommended by POULTER [1950], chiefly because of a lack of suitable detonating equipment.

For convenience in setting-up, a T spread was used, with an offset of 10 to 20 ft and a geophone spacing of 50 or 100 ft. Orientation of the geophone spread relative to the trend of crevasses seemed to have little effect on the recorded amplitudes of surface waves. Consequently the geophones were usually aligned east-west (perpendicular to the profile line) simply because this was the orientation of the smooth and easily-traversed ice "bands."

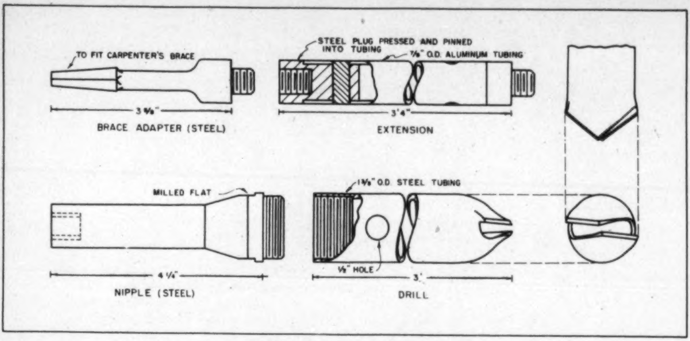


Fig. 2--Diagram of ice drill

(3) Electronic settings--Amplifier gains had to be kept low because of continual wind and the noise of water running in crevasses. No automatic volume control, expander, or mixing was used. Filters were set at 25-80 cps, the widest possible band-pass. Four of the amplifiers (1, 2, 4, and 6 in Fig. 3) were modified in the field for higher frequency response up to about 125 cps.

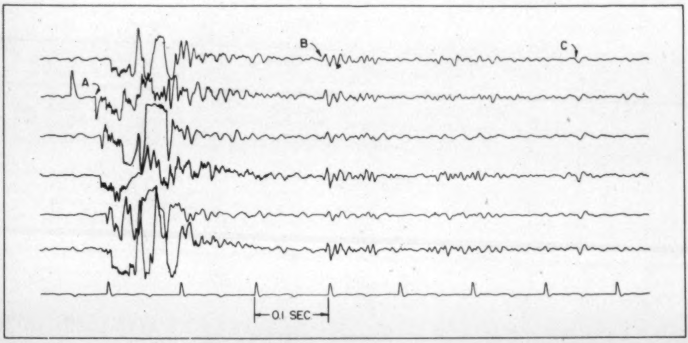


Fig. 3--Copy of seismic record 90 from station 15-S; "T" spread, 20-ft offset, 100-ft geophone interval, 2/3-oz charge at 26-ft depth; A, time break (earlier pip is cap make); B, bedrock reflection, 1930-ft depth; C, deeper sedimentary horizon reflection, 3700-ft depth

Interpretation of the seismic records--Refraction shots at Glacier Camp indicate a compressional wave velocity in this ice of 12,320 ft/sec, with a probable error of 30 ft/sec. Shotpoint to geophone distances ranged from 25 to 2133 ft, and the time-distance curve gives no evidence of increasing velocity with depth.

The constant velocity-with-depth relationship permits a simple arithmetic calculation of ice thickness based on shot depth, reflection time, and seismic velocity. Data for the various stations and the changes in ice thickness along the seismic profile are illustrated in Figure 4. It is noteworthy that the subglacial floor is below sea level along the entire seismic profile, reaching depths of more than 700 ft below sea level in the central part of the profile line. The ice becomes thinner both northward toward the mountains and southward toward the ice margin. No "step-out" was observed on any of the reflections from the ice-bedrock interface, suggesting a relatively smooth subglacial topography. Nothing was found corresponding to the horizontal velocity zones reported by GOLDTHWAIT [1936] in the Crillon Glacier.

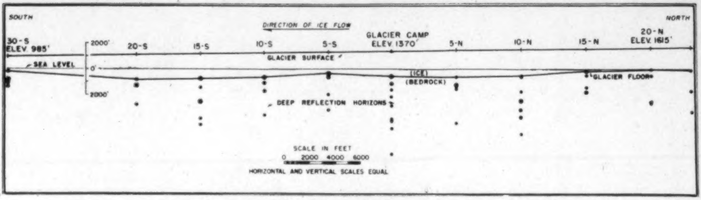
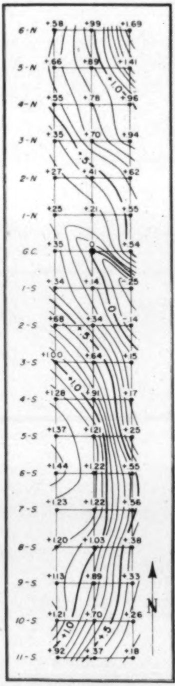

SOUTH
NORTH
DIRECTION OF ICE FLOW
30-S
ELEV 985'
2000'
20-S
15-S
10-S
5-S
GLACIER CAMP
ELEV 1370'
5-N
10-N
15-N
20-N
ELEV 1615'
SEA LEVEL
0'
GLACIER SURFACE
(ICE)
(BEDROCK)
GLACIER FLOOR
2000'
DEEP REFLECTION HORIZONS
SCALE IN FEET
0 2000 4000 6000
HORIZONTAL AND VERTICAL SCALES EQUAL

Fig. 4--Seismic profile across Malaspina Glacier; size of dot represents relative strength of reflection


6-N
+.58
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+.35
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+.94
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2-N
+.27
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+.62
1-N
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GC
+.35
0
+.54
1-S
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+.14
-.25
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2-S
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3-S
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+1.0
4-S
+1.28
+.91
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5-S
+1.37
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+.25
6-S
+1.44
+1.22
+.55
7-S
+1.23
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+.56
8-S
+1.20
+1.03
+.38
9-S
+1.13
+.89
+.33
N
10-S
+1.21
+.70
+.26
+1.0
+.5
11-S
+.92
+.37
+.18

Fig. 5--Gravity map; values in milligals, stations 1000 ft apart

Many of the records show reflections from horizons within the sedimentary section beneath the glacier. Neither amplitudes nor arrival times of these pulses are suitable for multiples. Depths plotted in Figure 4 have been computed by using 10,000 ft/sec as a plausible seismic velocity for the rocks exposed in the Yakataga area, which are assumed to extend eastward beneath the Malaspina Glacier. Analysis of all the deep reflections, some of which show a significant "step-out," suggests a north-dipping homoclinal structure, and this would be compatible with the regional structure mapped in the Yakataga district.

Gravity investigations

General statement--In order to test the suitability of gravimeter measurements for determining more detail in the subglacial topography, a network of gravity stations was set up from station 6-N to 11-S of the seismic profile (Fig. 4). This three-mile interval was chosen because seismic work had indicated a 300-ft ridge beneath station 5-S, and a gravity survey offered hope of better delineation of this feature. Theoretically, gravity measurements should produce definitive results because of the high density contrast between ice and rock.

Gravity procedure--A 54-station gravity network with a 1000-ft grid was set up as illustrated in Figure 5. The relative elevations of stations were measured with a microaltimeter loaned by the United Geophysical Co. This instrument had the advantage of speed and convenience over transit surveying, although peculiar meteorological conditions on the glacier necessitated lengthy computations and probably limited the accuracy to plus or minus one foot. An Atlas Exploration Co. Model F gravimeter was used, and the ruggedness and lightness of this instrument proved convenient. Leveling the gravimeter was a serious problem owing to differential pressure-melting beneath the supports, but this difficulty was partly alleviated by setting the tripod on a wooden board which had first been placed firmly on the ice surface. Drift correction data were obtained in the field by means of a looping-back pattern. Corrections for elevation and latitude were made in the normal manner, and the smooth surface of the ice and the distance of the mountains obviated the necessity of any terrain correction.

Gravity map--The corrected gravity readings are plotted and contoured in Figure 5. From this map, several conclusions may be drawn:

(1) The local trend of subglacial topographical features is apparently northwest-southeast. This is in contrast to the east-west orientation of structures within the ice along the profile line.

(2) Owing to this trend, a "two-dimensional mass" interpretation [HUBBERT, 1948] based upon a single north-south gravity traverse would give misleading results.

(3) Inasmuch as the gravity anomalies are relatively small, there is no reason to expect major relief on the glacier floor.

Configuration of the bedrock floor--Gravity at depth has been calculated by well-known methods described by EVJEN [1936] and BULLARD and COOPER [1948]. The second vertical derivative at each station along the center line may be approximated by using second differences and applying Laplace's equation. First vertical derivatives are calculated by assuming that each gravity reading is constant in a 1000-ft square surrounding that station and then integrating, applying the inverse-square law, in order to compute gravity 300 ft in the air over each center-line station. (With only three rows of stations, this height must be small relative to the distance between stations.) The first vertical derivatives may now be approximated by first differences, and it can be shown that the first derivative below the surface differs by only a constant from this value calculated for above the surface. With these computed values of the first and second derivatives, gravity may now be extended downward to any sufficiently small depth by a Maclaurin series, and the relief of a discontinuity at this depth, assuming a given density contrast, may be calculated as outlined by EVJEN [1936]. Figure 6 shows the detailed topography of the bedrock floor along the gravity profile, using seismic depths at Glacier Camp and station 10-S as the basis for depth extension and regional gradient correction. The results substantiate the relative smoothness of the glacier floor and verify the existence of a 300-ft ridge beneath station 5-S. Furthermore, this ridge is probably of bedrock and not due to local accumulation of subglacial drift. The discrepancy between the seismic and gravity depths at station 5-N is probably due to failure to pick the true bedrock reflection on the extremely poor seismic records from this station.

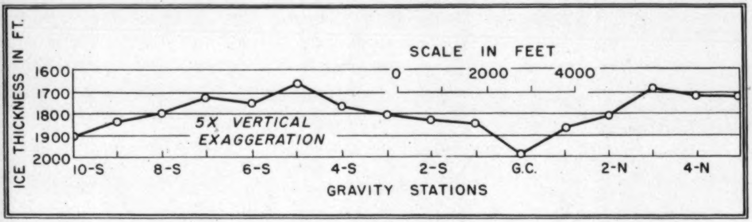

Fig. 6--Ice thickness between stations 10-S and 5-N on basis of gravity measurements

Comparison of seismic and gravity operations

The low relief of the glacier surface, together with the high density contrast between ice and rock, suggests that gravity measurements might be the best means of quickly determining ice thickness. The Malaspina operation, however, points up several drawbacks. Interpretation of gravity data requires that the ice thickness be known in at least one location, unless operations are close to the ice margin [LITTLEWOOD, 1952]. In most instances, this information could best be supplied by seismic techniques, and once seismic equipment has been moved onto the glacier, its continued use might be more efficient than switching to gravity exploration. Leveling the gravimeter on ice constitutes a serious problem, as does the accurate surveying and marking of stations. Lack of time and suitable office facilities, moreover, precludes full analysis of gravity data until long after field operations are concluded. Seismic calculations, on the other hand, are simple enough so that the effectiveness of the operation can be determined as it progresses. This argument takes on added importance in view of the isolated nature of glacier field studies. Seismic reflection shooting seems to be well suited for determination of glacier thicknesses, especially where the crevassing is not severe and the firn layer is thin or absent.

Seismic refraction shooting on proglacial deposits

Near the Beach Camp (Fig. 1) two refraction profiles were shot on the proglacial deposits with the hope of determining their thickness. Presumably, the bulk of this unconsolidated material outside the present margin of the Malaspina is glacial drift. At a maximum shot-point to geophone distance of 4500 ft, a break in the time-distance curve had not yet been reached. The measured shallow velocity was 6400 ft/sec, but conclusions as to the thickness of this layer depend upon an assumed velocity in the underlying bedrock. Minimum bedrock velocity inferred from the regional geology suggests a thickness of drift of not less than 500 ft. If bedrock is truly 500 ft or more below sea level at Beach Camp, the seismically-determined -150-ft level of bedrock at station 30-S of the glacier profile indicates a considerable bedrock lip near the present snout of the glacier. An alternative interpretation, perhaps geologically more reasonable, is that the shallowest reflection at station 30-S is not from bedrock but from the interface between ice and unconsolidated drift that lies beneath the glacier near its margin. Such a contact would have a very poor reflection coefficient, and the much stronger reflection from -800 ft at this location may well represent the actual bedrock surface beneath the drift.

Acknowledgments

The field work was done under the supervision of R. P. Sharp and the office work under C. H. Dix; both have criticized the manuscript and their guidance is gratefully acknowledged. D. L. Baker and G. P. Rigsby took considerable time from their own field projects to aid in the geophysical work. Valuable equipment was loaned by the United Geophysical Co. and the Atlas Exploration Co. The work was done under the sponsorship of the Office of Naval Research (Contract N6onr-244-16), the Arctic Institute of North America, and the California Institute of Technology.

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SMALL-SCALE TOPOGRAPHIC EFFECTS ON PRECIPITATION DISTRIBUTION IN SAN DIMAS EXPERIMENTAL FOREST

Joseph I. Burns

Abstract--The topographic parameters, elevation, slope, rise, aspect, and zone of influence are correlated with annual precipitation for the San Dimas Experimental Forest in a multiple-graphical correlation. From this relation it is possible to make an estimate of precipitation at any point in the Forest area with a greater degree of accuracy than when elevation alone is used. The correlation was developed from 11 years of record for 96 gages and a completely independent check was obtained from data for the same period of record for 45 gages which were not used in the graphical development. This study confirms Spreen's investigation for western Colorado and shows the same general technique of graphical correlation of precipitation with topographic parameters is applicable through a wide range of topographical and meteorological conditions.

Introduction--In storms produced by orographic lifting of air masses many topographic factors have considerable effect on the amount of water that will fall in a given location. If the topographic parameters can be defined, a more realistic picture of the areal distribution of rainfall can be developed than is possible solely on the basis of an elevation-precipitation relationship. Large-scale topographic effects have been extensively studied and defined with most studies having been restricted to the relationship of elevation to rainfall [BARROWS, 1933; JOHNSON and KERN, 1944; LEE, 1911; LULL and ALLISON, 1950; DONLEY and MITCHELL, 1939]. SPREEN [1947] developed coaxial relationships between precipitation and large-scale parameters, elevation of the station, a slope parameter, exposure of the station to the inflow of air masses, and orientation of this exposure for western Colorado. In order to show the effects of small-scale topography on rainfall distribution, the following graphical relationship between five topographic parameters and precipitation was developed for the San Dimas Experimental Forest, California.

Description of San Dimas Experimental Forest--The San Dimas Experimental Forest [KRAEBEL and SINCLAIR, 1940] located in the San Gabriel Mountains northeast of Glendora, California, was established in 1933 as a branch of the California Forest and Range Experimental Station of the United States Forest Service. The station was established to investigate the many factors of forest influences. The gross area of 17,000 acres within the boundaries of the Forest includes San Dimas and Big Dalton Creek drainage basins. The topography is rugged. In a distance of five miles the elevation ranges from approximately 1600 ft to 5400 ft. As part of the observational equipment in the Forest, 380 standard eight-inch rain gages were initially located in the area. Most of the gages were placed on contour trails that were spaced at approximately 500-ft elevation intervals. The distribution of the 141 gages used in this study is presented in Figure 1. The rain-gage density computed from the number of gages used in this study is one gage for every 0.15 sq mi as compared to the average rain-gage distribution for the United States of approximately one gage for every 250 sq mi.

Selection of data--The development of a correlation requires a sufficient amount of data to insure that the developed relationship has statistical significance. Records for 141 gages from 1935 to 1946 were used in this study. These records are from a sufficient number of stations to develop the relationship and also to give an adequate independent check of the developed correlation. The selected period eliminates any need to adjust or interpolate data. The annual rainfall at Glendora for the 11-year period averaged 99 pct of the 75-year normal. The average annual rainfall within the Experimental Forest ranges from approximately 26 to 40 inches. To insure that a random sample of stations was used in developing the relationship, a random number table was used to select 96 stations from which was developed the rainfall-topography correlation. The remaining 45 gages were used as check gages and were not used in the development.

Annual rainfall figures were used in the development of the graphical relationship. Approximately 80 pct of the annual precipitation occurs from December through April. Storms in this period are almost exclusively of the cyclonic type and during remainder of the year storms are predominantly of the convective type. Since the developed relationship of topography to rainfall more nearly fits the meteorological conditions that occur in a cyclonic disturbance, the correlation would probably have been improved if only the shorter period had been used.

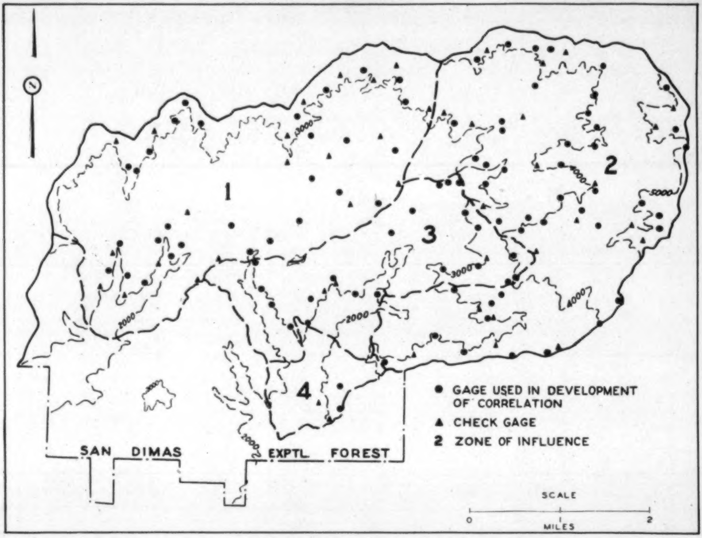

1
2
3
4
3000
2000
4000
5000
● GAGE USED IN DEVELOPMENT OF CORRELATION
▲ CHECK GAGE
2 ZONE OF INFLUENCE
SAN DIMAS EXPTL. FOREST
SCALE
0
1
2
MILES

Fig. 1--Rain-gage locations

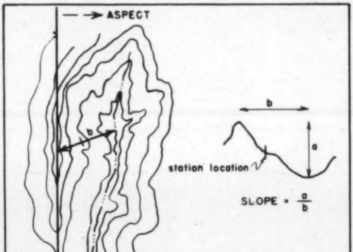

ASPECT
b
b
a
station location
SLOPE = a/b
RISE
0
1
2
3
4
5
miles

Fig. 2--Schematic sketch of parameters

Definitions and analyses of parameters--If an air mass is cooled below the dew point, water vapor will be condensed and precipitation may occur. In mountainous regions, air masses are forced to rise as they pass over the mountains. Since rate and amount of lifting control the condensation process, orographic lifting is a primary precipitation-producing mechanism. It can be assumed that topographic parameters are important controls on the amount of water that will be precipitated in a given location. The five parameters which were found to be important are the following. Figure 2 is a schematic sketch of the parameters called slope, rise, and aspect.

Elevation of the station expressed in feet above mean sea level. As an air mass rises in flowing over a barrier, it is cooled. This cooling, as noted above, results in condensation of the moisture. As the barrier height increases there is more chance for the condensation process to take place; therefore, for higher elevations we can expect a larger quantity of precipitation. However, the quantity of moisture in the atmosphere decreases with increasing elevation. These two effects may result in a precipitation maximum at some elevation below the crest of the barrier. The range in elevation in San Dimas Experimental Forest does not appear to be large enough to produce this effect and therefore we expect a continued increase in rainfall with elevation.

The slope of the ground surface along a line normal to the contours and passing through the station. The slope is taken as the average from valley bottom or change in downward slope to ridge top or change in upward slope; or within a distance of one-quarter of a mile each direction, whichever is shorter. The amount of precipitation in an area depends on the rate of precipitation formation. The rate of precipitation formation in turn depends upon the rate of lifting of the air mass. Steeper barrier slopes mean faster lifting. It follows that a greater amount of rain could be expected on the steeper slopes. The slope as used in this correlation may be too localized to represent the true lifting effect; however, it measurably improves the correlation.

The rise is the difference in elevation expressed in thousands of feet and is measured between the station and the highest point within a five-mile radius in the northeast quadrant. Streamlines of air flow are analogous to streamlines produced by water flowing around a barrier in an open channel. This effect results in the air mass being lifted upwind of the change in slope, hence the rise parameter was introduced to show this large-scale lifting effect. If a more effective slope parameter had been defined, perhaps this rise parameter could have been eliminated.

The aspect is the direction, to eight points of the compass, of a line normal to the ridge line and passing through the station, away from the ridge line. Storms in this area are predominantly from the southwest [U. S. WEATHER BUREAU, 1945] with only about 23 pct of the precipitation accounted for by storms from the north [HAMILTON, 1944]. The slopes facing the direction of the prevailing winds should receive a higher amount of precipitation than those slopes that are shielded.

The zone of influence is the geographic position within the San Dimas Experimental Forest as defined in Figure 1. It shows the effect of many topographic parameters not already defined and introduced into the correlation. It serves as an index to large-scale regional differences such as influence of a windward barrier, upwind effect from mountain ridges to the leeward, and other similar influences. A continued effort at defining parameters could possibly result in the elimination of, or a material reduction in, the influence of this generalized parameter.

Development of multiple-graphical correlation--The correlation (Fig. 3) was developed by multiple coaxial correlation methods essentially as described by LINSLEY, KOHLER, and

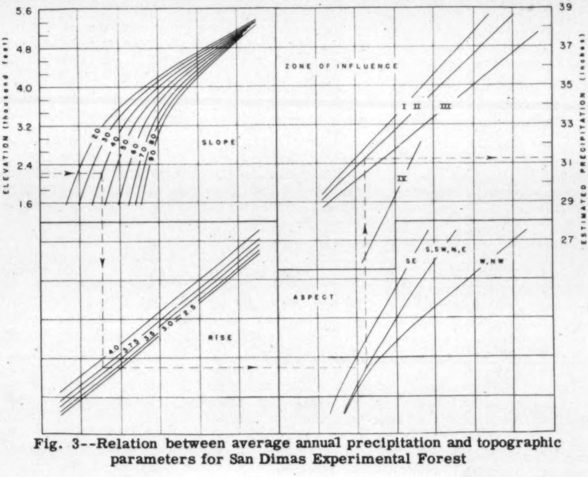


Fig. 3--Relation between average annual precipitation and topographic parameters for San Dimas Experimental Forest

PAULHUS, [1949]. The first two parameters introduced were elevation and slope. Elevation was laid off as the ordinate and actual rainfall as the abscissa; the points were plotted and labelled with the value of slope. To facilitate construction of curves, the points were grouped according to slope and averaged within elevation classes. First approximation curves which would best fit these group averages were drawn.

Rise, the next parameter, was introduced in the second quadrant, in which the horizontal axis was the estimated rainfall based on elevation and slope and the vertical axis was the actual rainfall. The points were plotted and labelled with the value of rise, and group averages with respect to rise and estimated rainfall were computed. A family of curves was fitted to these group averages.

The third quadrant was developed by plotting the estimated rainfall based on the first two quadrants against actual rainfall, which was then the horizontal axis. Each point was labelled with its value of aspect, and a family of curves was fitted by averaging groups of points according to aspect and estimated precipitation.

The final parameter was zone of influence, which was introduced in the fourth quadrant by plotting the estimated rainfall from the first three quadrants against the actual rainfall. After labelling the points, the group averages were determined and used to fit a family of curves representing the four zones.

At this point it was possible to return to any quadrant and use the data adjusted for the other parameters to see if a change in the family of curves in question was required. Adjustments are normally necessary because each curve-family is initially drawn without consideration of the effect of parameters subsequently introduced. To eliminate this influence from the first quadrant, the fourth quadrant was entered with the actual rainfall and the points projected through the fourth, third, and second quadrants with the appropriate values of the parameters to the first quadrant, where the points were plotted against elevation and labelled with their value of slope. Second approximation curves for slope were drawn, where necessary, to fit these adjusted points. The second quadrant was then adjusted by entering the fourth quadrant with the actual rainfall and projecting the points to the second quadrant where the points, which had also been projected through the adjusted first quadrant to the second quadrant, were plotted and labelled with their appropriate values of rise. The rise curves were drawn to fit these readjusted points. In like manner the third and fourth quadrants were adjusted.

A tabulation of the topographic parameters for the 141 gages is not included with this paper; however, the tabulation can be obtained by writing the author. The tabulation also contains the actual mean annual precipitation, estimates of annual precipitation based on the elevation-precipitation relationship, and estimates based on the graphical correlation.

Summary of other parameters investigated--Many possible parameters were investigated before arriving at the five that were included in the final graphical relationship. The following is a summary of parameters that were studied for correlation with rainfall distribution. A very small-scale slope that was previously determined by observation at each gage location by the Forest Service in the San Dimas area was tested. This definition gave a reasonably good fit to a family of curves, but a study of inconsistent points showed that the larger-scale parameter used in the final relation gave a better correlation. To give weight to the direction in which most of the storms approach the area, slope was also measured for the stations in the north-south direction, differentiating between southerly and northerly slopes. No correlation was evidenced from this definition.

Several definitions of exposure similar to that defined by SPREEN [1947] were investigated. The number of degrees in which there was no barrier higher than 500 ft within a distance of five miles was checked without success. The barrier height was then increased to 1000 ft with some improvement, but the improvement was insufficient to permit the use of this as a parameter. Applying Spreen's definition of orientation resulted in all points having the same orientation value which makes it unsuitable for this small-scale study.

A larger-scale slope parameter, degree of rise between the highest point in the northeast quadrant from the station and the highest point in the southwest quadrant, both of which were not over five miles from the station, had but slight correlation.

An aspect value that depended only on the immediate contours instead of the general direction of the ridge line was investigated without success.

The amount of precipitation that can fall on an area is directly dependent upon the quantity of moisture available in the atmosphere. If an air mass produces rain to the windward of an area, it follows that there will be less moisture in the air mass as it moves downwind. A barrier to windward may induce precipitation at that point and therefore the highest elevation windward from the area under study may be a significant parameter. To determine the barrier effect in the upwind direction, the difference in elevation of the highest point in the southwest direction from the station was determined and this value was divided by the distance from the station. Apparently little correlation existed with this definition. Another possible definition was the sum of the values determined by dividing the elevation of the highest points by the distance from the station in the south, south-southwest, southwest, west-southwest, and west directions. Since parameters using distance from the station met with little success, the elevation of the highest separate ridge more than one and one-half miles from the station was tested but was found to be unsatisfactory.

A barrier effect defined as the highest point in a southwest direction that was greater than two miles distance from the gage appeared to be significant and was inserted in the correlation but upon adjusting the curves the effect of the parameter was eliminated; therefore, it was omitted from the correlation.

Check of correlation--An independent check of the statistical significance of the multiple correlation was made possible by the abundance of data available. The index of multiple correlation for the 96 gages used in development of the relation is 0.84 and for the 45 independent check gages 0.82 as compared to 0.67 and 0.72, respectively, for the elevation-precipitation relation, (Fig. 4). Table 1 is a summary of the average error, standard error, and index of correlation for the gages which were used in developing the graphical relation and the check gages, and are computed for the elevation-precipitation and the multiple-graphical relations.

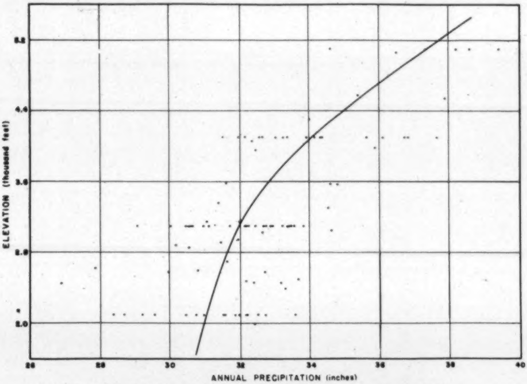
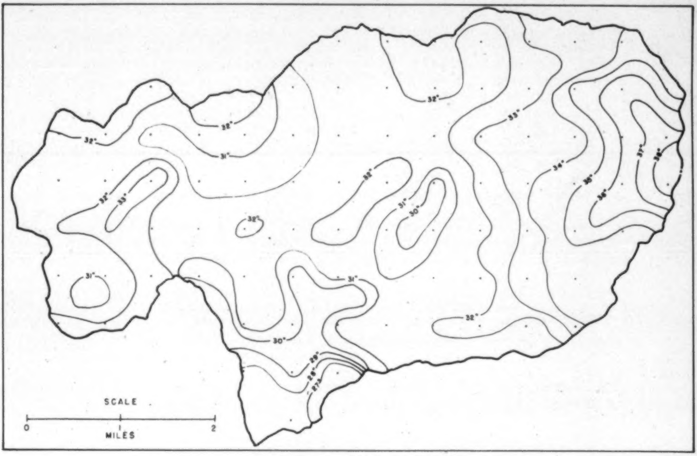


Fig. 4--Relation between average annual precipitation and elevation, based on period, 1935-1946

Table 1--Statistical summary

Item	Elevation-precipitation relation		Multiple-graphical correlation	
	96 gages used in development	45 check gages	96 gages used in development	45 check gages
Average error, inches	1.32	1.30	0.93	1.12
Standard error, inches	1.59	1.76	1.17	1.51
Index of correlation	0.67	0.72	0.84	0.82


32"
32"
31"
32"
33"
32"
32"
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30"
31"
32"
33"
34"
35"
36"
37"
38"
30"
32"
29"
28"
27"
SCALE
0
1
2
MILES

Fig. 5--Isohyets developed from graphical relation, 11-year mean annual precipitation, 1935-1946

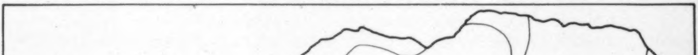
32"
32"
28"
32"
28"
28"
SCALE
0
1
2
MILES

Fig. 6--Isohyets from existing isohyetal map of San Gabriel Mountains and vicinity

The relation as developed is based on minimizing the average error rather than minimizing the standard error. The index of correlation is therefore not strictly applicable to the fitted curves. To arrive at the smallest standard error, least-squares curves would have had to be fitted to the data.

Isohyetal map development--The purpose of determining topographic parameters that influence precipitation is to more accurately determine the areal distribution of precipitation in areas where there are an insufficient number of gages. Assuming that the San Dimas Experimental Forest Area is such an area, an isohyetal map for this area was developed from the graphical relation. A grid on half-mile centers was laid out over the area. At each grid intersection the necessary parameters were measured and from the multiple-graphical correlation the precipitation at each point was estimated. From these points the isohyets in Figure 5 were constructed. The isohyets reproduced in Figure 6 were enlarged from an existing isohyetal map of San Gabriel Mountains and vicinity. The mean precipitation of the area as computed from Figure 5 is 32.1 inches compared to the mean precipitation from Figure 6, which is 28.1 inches. A comparison of the two figures also shows vividly the difference in apparent precipitation distribution when small-scale topographic effects are taken into account.

Acknowledgments--This paper is a condensation of a thesis submitted by the author in partial fulfillment of the requirements for the Degree of Engineer at Stanford University and was developed under the direction of Ray K. Linsley. The cooperation of the staff of the California Forest and Range Experiment Station at Glendora, California, and especially E. L. Hamilton, Forester, for making their basic data available, is acknowledged with thanks. The assistance rendered by Carl B. Meyer and William L. Horn of the California Division of Water Resources is also gratefully acknowledged.

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4440 G St.
Sacramento, California

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DISCUSSION

Walter T. Wilson (U. S. Weather Bureau, Washington 25, D. C.)--Burns has raised the question of the degree of universality of topographic parameters such as he has used. The Hydrologic Services Division of the U. S. Weather Bureau has successfully applied this general technique to the following areas: Colorado River basin, Big Horn River basin, Upper Snake River basin, and the New England-New York and Arkansas-White-Red Interagency basin areas, all as yet unpublished.

The varying physiography and atmospheric circulation of different regions have led not only to modification of the original parameters, as Burns has found, but to the evolution of additional parameters. These new parameters include distance from coast (moisture source), position on slope, and others for expressing land surface configuration by means of expressions using only a small number of statistical degrees of freedom. These additional parameters suggest physiographic rather than topographic adjustment.

Burns is correct in suggesting that part-year precipitation accompanying cyclonic storms has a different association with topographic parameters than convective precipitation has. The U. S. Weather Bureau's recent studies of rainfall on the Mogollon Rim (in Arizona) project [HIATT, 1953] show this explicitly.

An important need in the technique of making physiographic adjustment of precipitation records is a rationale for defining zones of environment. At present the technique is a compromise of two attitudes. One comes from the analyst's knowledge that he can improve his correlation by increasing the number (and gerrymandering the shapes) of the zones. The other attitude comes from his knowledge that in the process he runs the danger of using too many degrees of freedom and of losing generality if the zones are too numerous or too small. He is inclined to go as far as his scientific conscience permits him in breaking up the region he is studying. But he is disturbed by having no physical principles for a priori guidance; the process is essentially empirical, and trial and error. I would like to express the hope that physical principles may eventually evolve as additional experience is gained from wider application and from giving more consideration to general atmospheric and storm circulation, and condensation processes.

In his discussion of elevation as a parameter, Burns refers to the old question of an optimum elevation above which precipitation may diminish due to diminution of atmospheric moisture charge with increasing altitude. He concludes that the elevations in San Dimas Forest are not high enough to disclose or define such a limit. I would be inclined to extend his conclusion to the entire United States. In each of the areas listed earlier in this discussion we found that precipitation increased continually with elevation. Apparent diminution of precipitation with elevation above some optimum value may result from one or more of the following three influences: (1) confounding a coastside wet area such as the Olympic Peninsula of Washington with higher-elevation but drier continental areas in the same region; (2) the association of high-elevation sites with local parameters other than elevation that, without joint correlation, suggest elevation as a cause of light precipitation; (3) the association of deficient catch with the windiness that characterizes the ridge or pass exposure inherent with many high-elevation sites.

There are indications that physiographic adjustment can usefully be applied to frequencies and other measures of climate, in addition to mean annual and seasonal precipitation.

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STRESSES IN THE EARTH'S CRUST UNDER AN AXIAL SYMMETRICAL LOAD

H. S. Heaps

Abstract--Explicit formulas are obtained for the stresses produced in a thick plate by an arbitrary surface loading symmetrical about some vertical axis when the lower surface of the plate is supported in such a manner that, at any place, its vertical displacement is proportional to the vertical stress acting across it. By suitable choice of the constant of proportionality, the formulas may be applied equally well to a consideration of a thick slab supported by an elastic foundation and to the problem of the crust of the Earth subject to isostatic compensation. The formulas are applied to an estimation of the stresses in the lower portion of the Earth's crust during loading by an ice-cap.

Introduction--An approximate mathematical analysis of isostatic deformation of the Earth's crust due to a particular type of surface loading was given by JEFFREYS [1929], who considered the stresses produced by a sinusoidal mountain range of infinite extent. More recently, SNEDDON [1951] has obtained exact formulas for the stresses produced in thick plates by arbitrary loadings but has not treated the case in which the lower surface is supported by a yielding medium. In this paper explicit formulas are obtained for the stresses produced in a thick plate by an arbitrary loading symmetrical about some vertical axis when the plate is supported in such manner that the vertical displacement of its lower surface at any place is proportional to the vertical stress acting across it. By suitable choice of the constant of proportionality, the formulas may be applied equally well to the case of a thick slab supported by an elastic foundation and to the problem of the crust of the Earth subject to isostatic compensation. A reversal of sign throughout the formulas gives the stresses due to the removal of a load previously resting upon the upper surface. Gravitational stresses have been neglected throughout; the effect of their inclusion is discussed briefly at the end of the paper.

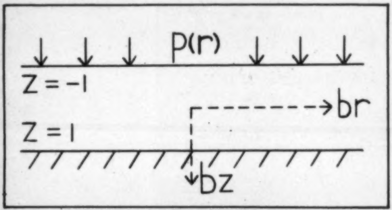

Fig. 1--Coordinate system

The formulas are evaluated, and the shearing stresses determined, at some 60 points near to the lower surface of the crust.

Theoretical formulas for the stresses--The plate or crust, as shown in Figure 1, is assumed to be of depth 2b, axes of bz and br being chosen as indicated. The plane $z = -1$ represents the upper surface of the plate which is subject to a loading $p(r)$ per unit surface area, while the plane $z = 1$ represents the lower surface whose displacement at any place is proportional to the vertical stress.

Assuming the plate to behave as an elastic material, then adopting the usual notation, the stresses may be written in terms of a single function $\Phi(r,z)$ as follows [SNEDDON, 1951]

$$\left.\begin{aligned}
\tau_z &= (3\lambda + 4\mu)\nabla^2\, \partial\Phi/\partial z - 2(\lambda+\mu)\, \partial^3\Phi/\partial z^3 \\
\tau_{rz} &= (\lambda + 2\mu)\nabla^2\, \partial\Phi/\partial r - 2(\lambda+\mu)\, \partial^3\Phi/\partial z^2\, \partial r \\
\tau_r &= \lambda\nabla^2\, \partial\Phi/\partial z - 2(\lambda+\mu)\, \partial^3\Phi/\partial r^2 \partial z \\
\tau_\theta &= \lambda\nabla^2\, \partial\Phi/\partial z - 2(\lambda+\mu)\, (\partial^2\Phi/\partial z\, \partial r)\, (1/r)
\end{aligned}\right\}\ldots\ldots\ldots\ldots\ldots(1)$$

where the symbol ∇^2 denotes the differential operator

$$\partial^2/\partial r^2 + \partial^2/\partial z^2 + (1/r)\,\partial/\partial r$$

and λ and μ are the Lamé constants of the elastic material of the crust. The symbol θ denotes an angle of rotation about the z axis. The displacements u_r, u_z in the r, z directions are given by

$$\left.\begin{aligned} \mu u_z &= (\lambda + 2\mu)\, b\nabla^2 \Phi - (\lambda + \mu)\, b\partial^2 \Phi/\partial z^2 \\ \mu u_r &= -(\lambda + \mu)\, b\partial^2 \Phi/\partial r \partial z \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (2)$$

The function $\Phi(r,z)$ may be determined as the solution of

$$\nabla^2 \nabla^2 \Phi = 0 \quad \ldots\ldots\ldots\ldots (3)$$

subject to the condition that the stresses and displacements given by (1) and (2) shall satisfy the following boundary conditions

(a) At $z = -1$, $\tau_{rz} = 0$, and $\tau_z = -p(r)$

(b) At $z = 1$, $\tau_{rz} = 0$, and $\tau_z = -ku_z$

where k is a suitable constant of proportionality.

Denoting the zero-order Hankel transform of $\Phi(r,z)$ by $G(s,z)$, then

$$G(s,z) = \int_0^\infty r\,\Phi(r,z)\, J_0(sr)\, dr$$

where $J_0(sr)$ is the Bessel function of order zero.

The transform of (3) is an ordinary differential equation in $G(s,z)$ and has the solution

$$G(s,z) = [A(s) + B(s)\,zs] \cosh zs + [C(s) + D(s)\,zs] \sinh zs \quad \ldots\ldots\ldots\ldots (4)$$

where A, B, C, and D are arbitrary functions of s.

Denoting $\partial G/\partial z$ by G', then the transforms of the first pair of (1) and (2) may be written in the form

$$\left.\begin{aligned} \int_0^\infty r\tau_z J_0(sr)\, dr &= (\lambda + 2\mu)\, G''' - (3\lambda + 4\mu)\, s^2 G' \\ \int_0^\infty r\tau_{rz} J_1(sr)\, dr &= \lambda s\, G'' + (\lambda + 2\mu)\, s^3 G \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (5)$$

$$\left.\begin{aligned} \mu\int_0^\infty ru_z J_0(sr)\, dr &= \mu b\, G'' - (\lambda + 2\mu)\, bs^2 G \\ \mu\int_0^\infty ru_r J_1(sr)\, dr &= (\lambda + \mu)\, bs\, G' \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (6)$$

Eq. (5) and the first of (6) may be substituted into the transforms of the boundary conditions (a) and (b), after which G may be replaced by (4). This procedure leads to four simultaneous linear equations to determine the functions A, B, C, and D. These equations involve very lengthy algebraic expressions which will not be reproduced here; the formulas finally obtained for A, B, C, and D are

$$\left.\begin{aligned} (\lambda + \mu)^2 A(s) &= -(s \sinh 2s + 2s^2 + 2c \sinh^2 s)(\lambda \cosh s + (\lambda + \mu)\, s \sinh s) \cdot F(s) \\ (\lambda + \mu)\; B(s) &= -(s \sinh 2s - 2s^2 + 2c \cosh^2 s) \sinh s \cdot F(s) \\ (\lambda + \mu)^2 C(s) &= \;\;(s \sinh 2s - 2s^2 + 2c \cosh^2 s)(\lambda \sinh s + (\lambda + \mu)\, s \cosh s) \cdot F(s) \\ (\lambda + \mu)\; D(s) &= \;\;(s \sinh 2s + 2s^2 + 2c \sinh^2 s) \cosh s \cdot F(s) \end{aligned}\right\} \quad \ldots\ldots (7)$$

where $F(s) = q(s)/\left\{s^3 [2s \sinh^2 2s - 8s^3 + c(\sinh 4s + 4s)]\right\}$, $q(s)$ being the transform of $p(r)$ as given later in (11), and

$$c = bk\,(\lambda + 2\mu)/[2\mu\,(\lambda + \mu)] = 2kb\,(1 - \sigma^2)/E \quad \ldots\ldots\ldots\ldots (8)$$

in terms of Poisson's ratio σ and the modulus of elasticity E.

Inversion of (6) gives

$$\left.\begin{aligned} \mu u_z &= b\int_0^\infty (\mu G'' - (\lambda + 2\mu)\, s^2 G)\, s\, J_0\,(sr)\, ds \\ \mu u_r &= b\,(\lambda + \mu)\int_0^\infty s^2\, G'\, J_1\,(sr)\, ds \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (9)$$

in which substitution for G, by virtue of the identities (4) and (7), leads to

$$(\mu/b)\, u_z = \int_0^\infty F_1\,(s,z)\, sq\,(s)\, J_0\,(sr)\, ds + (1/2)\,(1 - \sigma)\int_0^\infty F_2\,(s,z)\, q\,(s)\, J_0\,(sr)\, ds$$

$$(\mu/b)\, u_r = X = \int_0^\infty F_3\,(s,z)\, sq\,(s)\, J_1\,(sr)\, ds - (1 - 2\sigma)\int_0^\infty F_4\,(s,z)\, q\,(s)\, J_1\,(sr)\, ds$$

where

$$F_1(s,z) = \frac{s[(1+z)\sinh 2s \sinh (1-z)s + 2s(1-z)\sinh (1+z)s] + c[(1+z)\sinh 2s \cosh (1-z)s - 2\sinh (1+z)s]}{2s(\sinh^2 2s - 4s^2) + c(\sinh 4s + 4s)}$$

$$F_2(s,z) = \frac{s[\sinh 2s \cosh (1-z)s + 2s \cosh (1+z)s] + c \sinh 2s \sinh (1-z)s}{2s(\sinh^2 2s - 4s^2) + c(\sinh 4s + 4s)}$$

$$F_3(s,z) = \frac{s[(1+z)\sinh 2s \cosh (1-z)s - 2s(1-z)\cosh (1+z)s] + c[(1+z)\sinh 2s \sinh (1-z)s + 2\cosh (1+z)s]}{2s(\sinh^2 2s - 4s^2) + c(\sinh 4s + 4s)}$$

$$\left.\begin{aligned} F_4(s,z) \\ F_5(s,z) \end{aligned}\right\} = \frac{s[\sinh 2s \sinh (1-z)s \pm 2s \sinh (1+z)s] + c \sinh 2s \cosh (1-z)s}{2s(\sinh^2 2s - 4s^2) + c(\sinh 4s + 4s)}$$

the minus sign applying to F_4 and the plus sign to F_5 which is included for future reference.

In the subsequent application it is necessary to compute the stresses $(\tau_r - \tau_z)/2$, $(\tau_r + \tau_z)/2$, τ_{rz}, and τ_θ, which may be written as

$$(\tau_r - \tau_z)/2 = -\int_0^\infty s\,[\mu G''' - (2\lambda + 3\mu)\, s^2 G]\, J_0\,(sr)\, ds - Y/r$$

$$(\tau_r + \tau_z)/2 = (\lambda + \mu)\int_0^\infty s\,(G''' - s^2 G')\, J_0\,(sr)\, ds - Y/r$$

$$\tau_{rz} = \int_0^\infty s^2\,[\lambda G'' + (\lambda + 2\mu)\, s^2 G]\, J_1\,(sr)\, ds$$

$$\tau_\theta = \lambda\int_0^\infty s\,(G''' - s^2 G')\, J_0\,(sr)\, ds + 2Y/r$$

with Y denoting $(\lambda + \mu)\int_0^\infty s^2\, G'\, J_1\,(sr)\, ds$. Use of (4) and (7) then leads to the following identities for the required stresses

$$\left.\begin{aligned}
(\tau_r - \tau_z)/2 &= 2\int_0^\infty F_3\,(s,z)\, s^2 q\,(s)\, J_0\,(sr)\, ds - X/r \\
(\tau_r + \tau_z)/2 &= -2\int_0^\infty F_4\,(s,z)\, sq\,(s)\, J_0\,(sr)\, ds - X/r \\
\tau_{rz} &= -2\int_0^\infty F_1\,(s,z)\, s^2 q\,(s)\, J_1\,(sr)\, ds \\
\tau_\theta &= -4\sigma\int_0^\infty F_5\,(s,z)\, sq\,(s)\, J_0\,(sr)\, ds + 2X/r
\end{aligned}\right\}\ldots\ldots\ldots\ldots (10)$$

It may readily be verified that the above stresses do indeed satisfy the boundary conditions (a) and (b).

In order to evaluate (10) it is first necessary to calculate q (s) from

$$q\,(s) = \int_0^\infty p\,(r)\, r\, J_0\,(sr)\, dr \ldots\ldots\ldots\ldots (11)$$

In the case of a loading p (r) that is of constant amount w per unit area for r less than a value a, and zero for r greater than a, (11) becomes

$$q\,(s) = (aw/s)\, J_1\,(as) \ldots\ldots\ldots\ldots (12)$$

After calculation of the integrals (10), the three principal stresses and the maximum shearing stress at any point are given by

$$\tau_\theta \quad \text{and} \quad (\tau_r + \tau_z)/2 \pm [(\tau_r/2 - \tau_z/2)^2 + \tau_{rz}^2]^{1/2} \ldots\ldots\ldots\ldots (13)$$

Maximum shear stress = (maximum principal stress - minimum principal stress)/2

It is to be noted that when $k = \infty$, Eq. (10) are greatly simplified and apply to a plate whose lower surface rests on a perfectly rigid supporting medium. If k is put equal to zero, the formulas are again much simpler and apply to the case in which the lower surface is unsupported save at very large distances from the origin.

Application to the Earth's crust--The previous mathematical analysis was developed in order to investigate the stresses produced in the following system in which it is suggested that the stresses should be similar to those produced in the Earth's crust due to the weight of an ice-cap on the surface [DALY, 1934].

The crust is assumed to be of thickness 40 km and to have the elastic properties of granite, namely, a modulus of elasticity of 7×10^{11} cgs units, and a Poisson's ratio of 1/4. It is supported by material whose density is greater than that of the crust by one gm/cm^3, this being the density difference assumed by JEFFREYS [1929]. The consequences of this density assumption are discussed later. The shearing forces upon the upper and lower surfaces are considered to be negligible. After the lower surface has undergone isostatic compensation, any point in the initial plane of the lower surface experiences an upward force due to the weight of the supporting medium displaced, together with a downward force due to the weight of that lower portion of the crust that has sunk beneath the plane of the original lower surface. Accordingly, after the deformation has taken place, any point at the depth of the original lower surface is subject to an upward thrust of one gm/cm^2 of surface for each centimeter of vertical displacement. Thus, in dynes, $k = 10^3$, and c, from (8), is approximately 0.005.

The surface loading is assumed to be of constant magnitude w per sq cm over a circular area of radius 200 km, and to be zero outside this range. Eq. (12) then becomes $q\,(s) = 10w\, J_1\,(10s)/s$.

With the dimensions chosen as above, the diameter of the ice-cap is ten times the depth of the crust. It is suggested that the region of the crust below the center of the ice-cap and the region below the perimeter are sufficiently far apart that one might expect very similar stresses in the corresponding regions below an ice-cap of much larger radius. The stresses below the center of the ice-cap are due mainly to the weight of the cap and the isostatic compensation of the crust, while the stresses below the perimeter are largely due to the discontinuity of the surface loading. Thus the results obtained should not be invalidated in general application due to any unfortunate choice of dimensions in the particular example considered.

The numerical integrations involved in (10) are extremely tedious and it has been deemed sufficient to evaluate them for values of r from 1, 2, ..., 10 and of z from 0.5, 0.6, ..., 1.0, that is, in the lower quarter of the crust.

The maximum shearing stress, as given by (13), has been calculated at the above 60 points, and lines of constant maximum shear are shown in Figure 2 in which for clarity the vertical scale has been magnified by a factor of ten compared with the horizontal scale. The maximum shearing stress over the portion considered occurs at the lower surface of the crust and has a magnitude in excess of 3w over an area of radius approximately 75 km. This shearing stress decreases fairly rapidly with decrease in depth through the crust and so is likely to produce a purely local effect of failure within a dome-shaped region. Shear in this region is due primarily to the isostatic compensation of the crust.

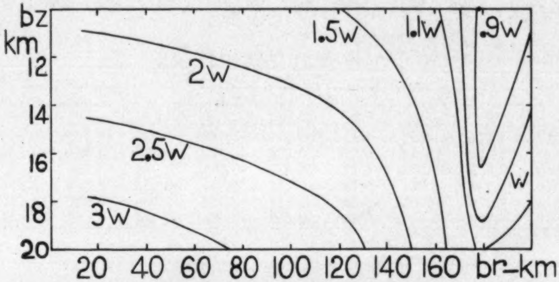

Fig. 2--Lines of equal maximum shear

As the radial distance outward increases, the shearing stress at points on the lower surface decreases until a radial distance of about 180 km is reached, after which it begins to increase again. The maximum shearing stresses have also been calculated on the lower surface at r = 11 and r = 15, the values being 1.9w and 2.1w respectively. This region of increased shear is due mainly to the discontinuity in the surface loading at the perimeter of the ice-cap. The decrease in magnitude of the shear with decrease in depth is not so rapid as in the central region and so

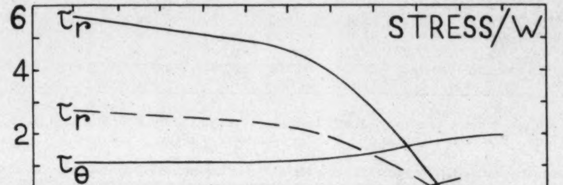

Fig. 3--Variation of stresses with radial distance

Table 1--Computed values of τ_r/w

z	r									
	1	2	3	4	5	6	7	8	9	10
0.5	2.747	2.650	2.553	2.448	2.376	2.194	1.848	1.284	0.551	-0.229
0.6	3.326	3.214	3.092	2.994	2.873	2.668	2.248	1.571	0.669	-0.257
0.7	3.890	3.772	3.634	3.516	3.390	3.144	2.660	1.866	0.786	-0.283
0.8	4.490	4.350	4.170	4.032	3.902	3.628	3.044	2.132	0.928	-0.300
0.9	5.078	4.896	4.704	4.556	4.412	4.110	3.496	2.468	1.081	-0.346
1.0	5.664	5.458	5.238	5.090	4.926	4.594	3.924	2.782	1.224	-0.360

Table 2--Computed values of τ_z/w

Z	r									
	1	2	3	4	5	6	7	8	9	10
0.5	-0.973	-0.938	-0.895	-0.834	-0.828	-0.796	-0.748	-0.667	-0.542	-0.440
0.6	-0.980	-0.952	-0.914	-0.874	-0.831	-0.794	-0.736	-0.657	-0.554	-0.446
0.7	-0.948	-0.938	-0.908	-0.872	-0.824	-0.776	-0.714	-0.636	-0.540	-0.443
0.8	-0.958	-0.936	-0.904	-0.860	-0.818	-0.764	-0.724	-0.652	-0.548	-0.432
0.9	-0.948	-0.928	-0.900	-0.866	-0.812	-0.754	-0.688	-0.608	-0.525	-0.440
1.0	-0.948	-0.930	-0.900	-0.850	-0.812	-0.754	-0.686	-0.608	-0.524	-0.460

Table 3--Computed values of τ_θ/w

z	r									
	1	2	3	4	5	6	7	8	9	10
0.5	-0.681	-0.639	-0.604	-0.575	-0.525	-0.443	-0.285	-0.024	0.316	0.648
0.6	-0.327	-0.295	-0.261	-0.232	-0.191	-0.125	0.025	0.270	0.587	0.891
0.7	0.023	0.052	0.079	0.104	0.131	0.194	0.330	0.559	0.857	1.133
0.8	0.370	0.381	0.414	0.427	0.450	0.504	0.637	0.847	1.125	1.376
0.9	0.720	0.737	0.756	0.761	0.776	0.824	0.937	1.147	1.399	1.622
1.0	1.074	1.088	1.097	1.094	1.102	1.150	1.245	1.429	1.672	1.867

Table 4--Computed values of τ_{rz}/w

Z	r									
	1	2	3	4	5	6	7	8	9	10
0.5	-0.074	-0.106	-0.097	-0.076	-0.108	-0.218	-0.391	-0.578	-0.700	-0.709
0.6	-0.062	-0.091	-0.083	-0.064	-0.091	-0.185	-0.334	-0.493	-0.599	-0.606
0.7	-0.050	-0.073	-0.067	-0.053	-0.072	-0.147	-0.266	-0.395	-0.480	-0.486
0.8	-0.036	-0.052	-0.047	-0.036	-0.049	-0.099	-0.182	-0.275	-0.337	-0.344
0.9	-0.019	-0.028	-0.025	-0.020	-0.026	-0.054	-0.099	-0.148	-0.180	-0.183
1.0	0	0	0	0	0	0	0	0	0	0

when failure takes place it is more likely to travel through the crust and consequently produce downpunching. For larger values of r the stresses tend to zero.

Assuming a shearing strength of 200 kgm/cm^2 for the material of the crust, then the crust will begin to shear at the lower surface at a radial distance of between 220 and 300 km when the load w reaches a magnitude of approximately 200/2 kgm/cm^2. With ice of density 0.9 gm/cm^3, this will occur for an ice-cap of height 1100 meters.

The variation of the stress components with respect to radial distance is shown in Figure 3. The full lines represent the stresses at the lower surface, while the broken lines represent those at three quarters of the depth. At the depths considered there is no radial stress at a radial distance of 175 km. For smaller radial distances the radial stress is one of tension and at greater distances is one of compression. This distance may be regarded as a measure of the amount of isostatic compensation and hence of the density difference between the material of the crust and that of the supporting medium. For a perfectly rigid supporting medium this distance is zero, while for an unsupported crust it is infinite. The graph of τ_z shows that, in the present example, the part of the crust directly below the ice-cap supports about 70 pct of its weight, the remainder being transmitted to the outer portions.

The computed values of τ_r, τ_z, τ_θ, τ_{rz} used in the plotting of Figures 1, 2, and 3 are given in Tables 1, 2, 3, and 4. It is seen that the discrepancies arising from the numerical integrations are of the order of one per cent.

Concluding remarks--It has been assumed that the density difference between the supporting material and the material of the crust is one gm/cm^3. While this is the figure assumed by JEFFREYS [1929], it has been suggested that a value of 0,3 gm/cm^3 might be more appropriate. The resulting change in the stresses would be greatest in the region of shear at the lower surface of the crust directly below the center of the ice-cap, while the region below the perimeter would be affected to a lesser degree, and it is reasonable to expect that the shearing stresses there would be of the same order of magnitude as in the example of this paper.

Stresses in the crust prior to addition or removal of the ice-cap have been neglected since it is difficult to estimate their magnitude. These include stresses caused by gravity, cooling of the crust, erosion, etc., and should be superposed on those obtained in this paper. The deformation may change the value of such stresses. For example, if gravitational stresses are taken into account, the deformation of the upper surface reduces the load upon the plane $z = -1$ by the weight of material that has passed from above to below. However, the previous formulas still apply provided w is used to denote the applied surface load per unit area minus the weight of material between the initial and final positions of the upper surface. With this interpretation of w, and a crust of density three gm/cm^3, the calculated stresses apply to the dome-shaped ice-cap shown by a full line in Figure 4. This figure is only approximate; instead of repeating the calculations to find the displacements at the upper surface, the values obtained at the lower surface from the relation $u_z = -\tau_z/k$ have been used as both sets of displacements are of a similar order. Without repeating the calculations it is possible to estimate that, on the assumption of a density difference of 1/2 gm/cm^3 at the lower surface, the displacements will be approximately one-half of those previously calculated, and an ice-cap as indicated by the broken line of Figure 4 will produce similar stresses in the lower part of the crust at radial distances of 200 to 300 km.

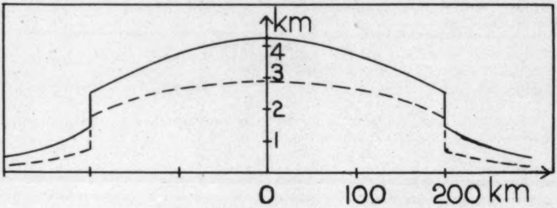

Fig. 4--Ice-cap profile allowing for gravitational effect

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open for formal discussion until March 1, 1954.)

Transactions, American Geophysical Union Volume 34, Number 5 October 1953

GEOSYNCLINES

W. Werenskiold

It is a well-known fact that a whole series of narrow, deep trenches stretch along the coasts of the Pacific in front of folded mountain chains. But, while the zone of Tertiary mountain folds is practically continuous from the southernmost point of South America to Bering Strait, and further over the island chains to New Zealand, the deep trenches are distributed in a discontinuous manner.

The deep trenches are mostly situated off deserts or chains of small islands, and are wanting off coasts of larger lands with copious precipitation.

Obviously some causal connection exists between the distribution of Tertiary zones of folding, and the formation of trenches. Why do not these latter form a continuous belt, like the mountain chains?

It may be because the trenches have been filled up by sediments off certain coasts, coasts with a great supply of products of denudation, with many rivers, carrying heavy loads of sand and gravel towards the sea. At places where very little or no material at all is being transported to the sea, that is, off deserts or chains of tiny islands, the trenches will remain for a long time.

Trenches which have become filled up by sediments form what the geologists call geosynclines. Both open and filled-up geosynclines seem to occur along the boundary between two slabs of the Earth's crust, the lighter one being pushed forth and above the other and the heavier one, which is depressed with respect to the lighter, along the rim. The distribution of earthquake centers does not disagree with this proposition.

Several objections may be made; for instance it is not certain that the deserts have been fixed in their present positions for a sufficiently long time to permit the filling up of the trenches at other places.

By modern methods it should be possible to ascertain, whether a filled-up trench exists, for instance, off the coast of British Columbia.

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Transactions, American Geophysical Union Volume 34, Number 5 October 1953

REPORT OF THE COMMITTEE ON SNOW, 1951-1952

Forrest L. Rhodes, Chairman

Henri Bader
Martin E. Baudendistel
Walter U. Garstka
George O. Guesmer
Clyde E. Houston
Duart A. MacLean
James C. Marr
Walter T. Wilson

The report of the Committee on Snow consists of brief reports from the various members of the Committee. Comments have been summarized inasmuch as the report for 1950-1951 was a comprehensive report covering the activities in research on snow on a national and an international basis. This report is an effort to bring matters to a fairly current point as related to the previous report.

Henri Bader (Snow, Ice, and Permafrost Research Establishment, Wilmette, Ill.)--The organization (SIPRE) is operated by the Corps of Engineers for the Department of Defense with headquarters and refrigerated laboratories occupying a three-story building at Wilmette, Ill. Besides the immediate and continuing task of gathering all available information on snow, ice, and frozen ground, and giving advice on the military aspects of these substances to the Armed Forces, SIPRE is doing scientific and engineering research. SIPRE experiential research on snow covers a wide field, including: (1) measurement of all pertinent physical properties of single ice crystals as a function of temperature (laboratory), (2) determination of the structure and physical properties of snow (laboratory and field), (3) study of snow metamorphism, that is changes in structure and physical properties (laboratory and field). Research papers are issued by SIPRE for distribution to Government agencies. Results of research will also be published in scientific journals.

George M. Jemison (Director of the Northern Rocky Mountain Forest and Range Experiment Station, U. S. Forest Service, Missoula, Montana, for Martin E. Baudendistel)--The snow studies at the Priest River Experimental Forest, Benewah County, Idaho, were established in 1948 with the specific objective of answering some of the questions confronting the development and evaluation of the flood-control program for the Upper Columbia River. This objective was met to the fullest degree possible under the circumstances, and the field work and analysis of the data were discontinued in May, 1952. Considerable data remain to be analyzed and reported.

The Priest River activities included (1) observations of the influence of forest cover on snow accumulation and melt under a variety of elevations, aspects, and slope positions, and (2) study of the hydrology of a 960-acre heavily timbered watershed. Precipitation was measured by 25 gages and 15 snow courses. Air temperature and wind records were obtained concurrently at six locations within the gaged watershed and at nine other locations within or near the watershed at various times. Two precipitation gages and a streamflow recorder have been operated within the gaged basin since 1938. Electrical soil-moisture and temperature installations were maintained at five sites.

Wm. L. D. Bottorf (Technical Director, Snow Investigations, Corps of Engineers)--Program operations since July, 1952, have centered primarily about analysis of data collected at the three snow laboratory basins which had been set up to obtain data for hydrologic studies, and particularly about special observations and analyses of data obtained in 1952 at snow-melt lysimeters at Central Sierra Snow Laboratory. In cooperation with SIPRE, extensive data were collected on changes in snow-pack temperature, depth, density, and structure, and on attendant hydrometeorological conditions at that laboratory. Analytical efforts were pointed toward establishing criteria for computing, through the thermal budget approach, the amount of melt that may be expected from a point in an open, unforested area. The studies embraced both clear-weather melt and rainy-weather melt, although data for the latter were limited in quantity. Several research notes and reports were completed during the year. Under Civil Works Investigations Project CW-170, which concerns the development of a radioisotope, radiotelemetering snow gage, the initial field testing program was satisfactorily completed at Central Sierra Snow Laboratory, and testing of the developed equipment is continuing in the Kings River drainage basin above Pine Flat Dam. Under project CW-171, analytical work on hydrologic projects of the Corps of Engineers and training of engineering personnel in snow hydrology were continued.

Walter T. Wilson (U. S. Weather Bureau, Washington, D. C.)--The Cooperative Snow Investigations, as a joint program of the Corps of Engineers and U. S. Weather Bureau, officially terminated June 30, 1952. The two agencies are continuing informal collaboration in their respective investigations.

The Soil Conservation Service, the State of California, and the U. S. Weather Bureau have begun a program of collaboration in seasonal water-supply forecasts. The forecasts are now being published jointly, and good progress is being made in the development of procedures for use of observations of both winter precipitation and snow-pack water equivalent.

The Bureau is continuing its study of sampling, observational methods, and physical processes of the snow-pack for improvement of its streamflow forecasting service.

Fred A Strauss (State of California, Division of Water Resources, for J. C. Marr)--The snow studies current and continuing in California are:

(1) Development of temperature-runoff relationship so as better to forecast the amount of April through July runoff as the season progresses. This includes relationship of daily temperature and stream hydrographic fluctuations (Division of Water Resources).

(2) The study of interrelationship of precipitation, snow-pack, soil priming, and resultant runoff in a multiple-graphical correlation continues (Division of Water Resources).

(3) Aerial photographs of snow-depth markers are being gathered to obtain sufficient data to allow a development of forecast method by this technique (California Electric Power Co. and Southern California Edison Co.).

(4) Aerial oblique photographs are now being taken so that elevation of snow line in the major basins of the Sierra can be determined. Snow-line elevation effect on snowmelt characteristics will then be evaluated (Los Angeles Dept. of Water and Power).

(5) In addition to this, a final paper on High Sierra Snow Ablation Observations was presented to the Western Snow Conference, April 21, 1953. This study, conducted by Walter T. Wilson, Richard D. Tarble, Oliver Kehrlein, and Eugene Serr, Jr., was for the purpose of determining the portion of snow ablation chargeable to evaporation at high elevations. Two separate series of observations determined that approximately ten per cent or less evaporated.

Corps of Engineers, South Pacific Division (F. L. R.),
San Francisco, California

(Manuscript received May 12, 1953; presented by title at the Thirty-Third Annual Meeting, Washington, D. C., May 4, 1952; open for formal discussion until March 1, 1954.)

REPORT OF THE COMMITTEE ON PRECIPITATION, 1952-1953

William C. Ackermann, Chairman

Eugene Bollay	William E. Hiatt	E. E. Sanderson
Henry Demboski	T. W. Kleinsasser	Franklin F. Snyder
David E. Donley	Sol D. Resnick	G. E. Stout

This Committee has been active as individuals and as a group in stimulating research in its field, urging presentation of worthwhile reports, and reviewing and analyzing papers both before and after publication.

Basic research continues in the field of measurement and transmission of precipitation data. This includes such subjects as improved design of rain gages and wind shields. Improved methods of testing make it possible to carry on these studies with greater efficiency.

Improvements have been and are being made in remote registering gages using telephone and radio transmission. These will lead to improved information on precipitation in remote locations. Tests on wind shields improve measurements, and here again such modern aids as wind tunnels greatly speed and improve our ability to test. A new development which has proven itself is the radio-isotope snow gage which can measure the water equivalent of snow on the ground and radio its reading to a remote station.

Another fascinating new development which has been reported in the literature during the past year is the use of radar. Stout, of this Committee, who is associated with the Illinois State Water Survey where this work is going on, says that results are encouraging as it appears that radar can measure mean storm rainfall with an accuracy comparable to a concentrated rain gage network.

Other studies leading to refinement of understanding of rainfall distribution like local exposure of gages and effect of slope and elevation continue at many centers of investigation. Office analysis studies such as methods of estimating missing records and use of double mass curves continue to appear in the literature.

A subject which has received considerable interest in the past year is the accuracy of measurement of precipitation over a given area. Perhaps this problem was not of concern in years past when areal measurements were almost universally based on too small a sample. Accuracy of measurement may also be influenced by the introduction of statistics into our field which facilitates the determination of the errors involved with various gage concentrations. Linsley and Kohler, Sanderson and Johnstone, and Huff and Stout have reported on this subject. Currently a similar study is under way in the TVA area.

Attention is called to a recent paper in the Transactions, "Cube-root normal precipitation distributions," by C. K. Stidd. In this novel and important report, the author points out that by converting rainfall amounts to the cube roots they follow the normal distribution. This is true for daily, monthly, or annual data. This writer has since applied this technique to storm rainfall amounts with success. As few as 15 storm observations appeared to have normal distribution.

An important significance to all this is that most statistical theory is based on the normal distribution. It would seem that a way has now been opened for application of this valuable tool to our science. It is our opinion that we have too long shied away from statistics when we could have done better work through use of it.

In recent past years this Committee has made reference to recording rainfall data by the U. S. Weather Bureau Hydroclimatic Network. Processing and publication of the hydroclimatic data were resumed late in 1952 after a lapse of about one year. The present publications, which are in a somewhat different form than originally, begin where the old publications stopped. This makes the published data approximately one year late, a situation which cannot be corrected under the present financial limitations. As a matter of fact, unless some supplemental financing is arranged, we will continue to get farther behind, since present funds permit the processing and publication of only about nine months' data per year.

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(Manuscript received May 20, 1953; presented at the Thirty-Fourth Annual Meeting, Washington, D. C., May 5, 1953; open for formal discussion until March 1, 1954.)

Transactions, American Geophysical Union Volume 34, Number 5 October 1953

REPORT OF THE COMMITTEE ON INFILTRATION, 1952-1953

L. L. Harrold, Chairman

1953	1954	1955
Don Kirkham	L. L. Kelly	E. H. Kidder
Leon Lassen	Wm. P. Martin	P. B. Rowe
Leonard Schiff	Howard Matson	N. L. Stoltenberg

Reports which have been received from most of the Committee members are presented below in abstract. Full manuscripts of some of the separate reports are on file in the office of the Union.

R. H. Burgy and J. N. Luthin (University of California, Davis, Calif.) presented a paper "A test of the single- and double-ring type of infiltrometer," February 8, 1952, at the Pacific Southwest Regional Meeting at Pasadena, California. They reported that single- and double-ring infiltrometer runs were made on uniform soil on a five-foot grid in a 40 × 90 ft basin that had been recently flooded four times. About 120 rings were used on each of four basins. The single ring was of six-inch diameter. The double ring was obtained by placing a 12-inch diameter ring concentrically around the six-inch ring. Both types of ring infiltrometers gave practically the same values on this wet uniform soil. This may not be true for stratified soils where lateral flow may be an important factor. Six ring infiltrometers under these conditions randomly spaced gave an average value that was within 30 pct of the true mean.

Harry F. Blaney (U. S. Soil Conservation Service, Los Angeles, Calif.)--The Soil Conservation Service in cooperation with the Ventura County Flood Control District has conducted field investigations to locate areas where soils are suitable for water spreading to replenish declining ground-water supplies. Infiltrometer tests were made on soil surfaces ranging in size from 64 sq in to 0.001 acre. Runs varied from a few hours to 120 days. It was found that small-area infiltrometer results needed to be modified considerably for application to large-area spreading ponds. On the latter, percolation rates appeared to be about one-fifth the infiltrometer value.

Leonard Schiff, E. S. Bliss, and C. E. Johnson (submitted by Leonard Schiff, U. S. Soil Conservation Service, Bakersfield, Calif.)--The following papers have been prepared for publication:

SCHIFF, LEONARD, An exploratory study of the effect of surface head on infiltration rates under water-spreading conditions, presented at meeting of The American Geophysical Union, Washington, D. C., May 7, 1952 [Trans., v. 34, pp. 257-266, 1953].

SCHIFF, LEONARD, Some developments in water spreading, mimeographed, September, 1952.

These studies pertain to soil treatments and operational procedures that increase and sustain infiltration rates over the normal rates of controlled water-spreading areas. The primary interest is to replenish ground-water supplies to meet irrigation requirements.

Surface heads greater than normally used may economically increase infiltration rates. Treatments with low initial cost or those having a cash return, as a hay or forage crop, are sought. In some areas, where subsurface soil horizons of low permeability limit the percolation rate and thus the infiltration rate, treatments are considered that affect such horizons. Here there is being tested such practices as (1) chiseling, (2) gravel-filled shafts, with and without top filters, with and without chlorination, and (3) in some instances Krilium sprayed on the interface between the soil and gravel. Surface soil treatments to be tried in the future include chlorination, Krilium, Krilium and pumice mixed, oil spray, alfalfa plus sheep fescue followed by water spreading after three years, and other grasses.

It usually takes a few water-spreading seasons for organic residues and grass to increase infiltration rates since organic residues must be well decomposed and grass sod must become established. In contrast, Krilium applied at a rate of 0.1 pct to a depth of three inches on a pond of 218 sq ft, acted shortly after application to increase and sustain infiltration rates greatly over rates obtained on untreated soil. Present infiltration rates of the Krilium pond after six months of submergence are about four feet per day. Four feet per day is about the maximum rate achieved on an untreated pond with subsequent decline to about 0.3 foot per day in six months. It is planned to treat an area of one-half acre with Krilium. The effect of all treatments and operational procedures on infiltration rates will be reported.

Cooperators in these investigations are the Kern County Land Co., the North Kern Water Storage District, the U. S. Bureau of Reclamation, the California Agricultural Experiment Station, the California State Division of Water Resources, and the Soil Conservation Service, Research, U. S. Department of Agriculture.

J. H. Dorroh (U. S. Soil Conservation Service, Albuquerque, New Mexico)--During the past 10 to 12 years, the Soil Conservation Service (Region 6) has conducted nearly 1000 infiltration runs primarily in Arizona and New Mexico. Among the uses to which these data were put are flood-survey programs in the Pecos, Rio Grande, Gila, Arkansas, and Fountain watersheds. Infiltrometer runs were made at field sites representative of each plant-soil group and for various conditions of cover density, vigor of plants, and erosion activity. Infiltration values which were then assigned to a particular set or sets of conditions were used in deriving estimates of excess rainfall (equivalent runoff) for flood-control programs.

The first infiltration runs, conducted in the early forties, were made with the type F and FA infiltrometers. In 1949, after reactivation of the flood survey program, C. H. Diebold, soil scientist, developed a modified type F infiltrometer which has been used on subsequent runs. This more recent equipment is described in an article entitled "Soil layers causing runoff from hard-land wheat fields in Colorado and New Mexico" [J. of Soil and Water Conserv., v. 6, no. 4, Oct. 1951].

Don Kirkham (Iowa State College, Ames, Iowa)--Three infiltration projects are active. One, infiltration curves are being derived from rainfall and runoff records from a few western Iowa streams. Another, measurements of infiltration are being made on terraces. The third, permeability values made for numerous Iowa soils are being correlated with soil drainage, a factor influencing infiltration.

P. B. Rowe (California Forest and Range Experiment Station, Glendora, Calif.)--Studies to determine the influences of various types of native vegetation on infiltration are being continued as a part of the lysimeter and plot experiments carried on at the San Dimas Experimental Forest in Southern California. Measurements of precipitation, surface runoff, soil moisture, and related phenomena are taken on 26 large lysimeters in which five separate shrub species, a pine species, a bunch grass association, and a bare soil are being studied. Some results have been published by E. A. Colman and E. L. Hamilton, "The San Dimas lysimeters," California Forest and Range Experiment Station, Research Note 47, 1947; multilithed. Similar measurements have also been started on several 1/40-acre surface runoff plots, three with a 32-year-old brush cover, three with a 25-year-old pine cover, and six with an annual grass cover. Infiltration determination on the plots will be supplemented by a series of North Fork infiltration tests employing both natural and artificial rainfall. Results of the lysimeter and plot studies are to be reported as they become available.

Veihmeyer and his associates at Davis, California, are continuing infiltration research. Finley B. Laverty is doing similar work with the Los Angeles County Flood Control District.

Donald E. Whelan (U. S. Forest Service, Upper Darby, Pa.)--A method of deriving estimates of surface runoff on a watershed basis by using infiltration values computed from values of retention and detention storage, percolation rates, and transmission velocities for the various soil horizons has been developed. These values were obtained from a laboratory study of soil samples taken by horizons under the principal soil-cover complexes. The infiltrometer was not used because, for numerous combinations of soil and cover it is very costly, its results are difficult to interpret and use, and the rates thus obtained are valid only for the particular complex on which the runs were made. The routing procedure provides a means of obtaining estimates of infiltration and surface runoff for any soil profile and for any rainfall pattern regardless of its variations in intensity and duration. This procedure was reported in "A method of determining surface runoff by routing infiltrated water through soil profiles" by Donald Whelan, Lemuel E. Miller, and John B. Cavallero, and will be published in the Transactions.

W. G. McGinnies (Director, Rocky Mountain Forest and Range Experiment Station, U. S. Forest Service, Fort Collins, Colo.)--Infiltration research at the Rocky Mountain Forest and Range

Experiment Station has been conducted by means of a portable infiltrometer, type FA, known as the Rocky Mountain infiltrometer. The use of the Rocky Mountain infiltrometer for measuring infiltration is described elsewhere [WILM, 1941 and 1943]. The design and operation of the infiltrometer have been described more recently by DORTIGNAC [1951]. All studies of infiltration have been carried out on plant-soil complexes. That is, plots have been randomly located in such complexes as grassland-shale soil, sagebrush-shale soil, or timber-litter-granitic soil. The selection of the plant-soil complex for study is the first step in determining infiltration.

Most of our studies have been designed to determine the influence of different kinds and amounts of vegetation on infiltration. Often tied into the studies is the effect of existing livestock grazing. To measure the influence of vegetation on infiltration, the f_c has been customarily used for comparative purposes. The f_c used here is considered to be the average infiltration rate during the last 20 minutes of a 50-minute run. It is during this 20-minute period that infiltration is generally stable and does not fluctuate greatly.

When comparing the infiltration of plant-soil complexes, it is desirable to know whether the f_c actually represents a plant or a soil influence, or both. Several investigators have used the f_c as the base for comparison. In our studies, we have questioned whether or not some other point or segment on the infiltration curve might more adequately represent the influence of vegetation on infiltration. We have set up the hypothesis that the f_c is mainly a function of some physical property of the soil and that infiltration is dominated by vegetation only during the early part of the run. See LASSEN and Others [1952] for further discussion of these relations.

Average infiltration curves for a grassland growing on shallow soils derived from biotite schist are used to illustrate this hypothesis. Twelve plots were randomly located in an area where the grass cover was poor and another 12 plots in an adjoining area of good-grass cover. The poor-grass plots were low in density and included such species as cheatgrass-brome, needle-and-thread, and blue grama, while the good-grass plots were high in density and consisted of such species as Parry danthonia, little bluestem, mountain muhly, and Idaho fescue. It is commonly expected that on those areas where good grass occurs, the f_c will be high when compared to areas where the grass is poor. In this example the reverse was true. The poor grass had a higher final infiltration rate with the average time from start to stability being 21.7 minutes. Similar time for good-grass plots was 30.1 minutes.

In addition to the infiltration runs on the 24 plots, soils information was obtained on 12 of the plots. Soils analyses were made of six plots in the poor grass and six in the good grass. The soils information included mechanical analyses of the surface (to two-inch depth) and of the subsurface three- to seven-inch depth, and seven inches plus). The analyses also included determination of pore sizes, bulk density, and percolation rates of the two depths.

To find some explanation for the reversal of the final infiltration rates between the good and poor grass areas, all of the plots were considered a part of the same grassland-schist soil complex. Several different combinations of statistical analyses were tried and Table 1 summarizes the most reasonable relationships upon which to base an explanation.

From the statistical analyses of this grassland growing on biotite-schist soils, it appears that the vegetation effects on infiltration ceased after the final infiltration rate leveled off. The effects of grass were first noticed during the period before the start of runoff. This initial time is related to the amount of litter or dead grass materials on the soil surface. The live grass continued to have an effect by prolonging the time from the start of runoff to the point where the final infiltration rate was relatively constant. In this example, good grass exerted a longer period of influence than did poor grass. Thus, the plots on which good grass occurred showed a noticeable effect on infiltration.

The example and statistical analysis explain the difference in the f_c between the two areas; that is, the per cent of clay in the subsurface soil governed the final infiltration rate. This is more satisfactory than to explain the f_c by differences in grass density (X_3), herbage (X_1), or condition (X_7). Actually, the relation between these vegetative factors and the f_c is negative, indicating that the poorer the vegetation, the higher the infiltration rate (f_c).

Should this type of analysis prove applicable to other plant-soil complexes, then a new base for comparison will be established. The analysis points directly to the role of vegetation in delaying surface runoff from cloudburst storms, and it should aid in the prediction of runoff and in the de-

Table 1--Summary of major analyses of influence of various factors on infiltration

Dependent variable	No. of plots	Independent variables with correlation coefficients[b]								Multiple correlation coefficient R	Independent variable[c]
		X_1	X_2	X_3	X_4	X_5	X_6	X_7			
Y	24	-0.6626[d]	-0.0205	-0.6656[d]	0.4703[e]	-0.1445	-0.3944	-0.6590[d]	....	0.7134[d]	None
		X_8	X_9	X_{10}	X_{11}						
Y	12	-0.1397	0.0554	0.1036	0.4353	....	....	....	....	0.5761	None
		X_{10}	X_{15}	X_{13}							
Y	12	0.1021	-0.8287[d]	0.2711	....	....	....	....	....	0.8592[d]	X_{15}
		X_{13}	X_{15}								
Y	12	0.2711	-0.8287[d]	....	....	....	....	....	....	0.8481[d]	X_{15}
		X_{15}	X_3								
Y	12	-0.8287[d]	-0.6961[e]	....	....	....	....	....	....	0.8668[d]	X_{15}
		X_5	X_3	X_1	X_2	X_{14}	X_{15}	X_{12}	X_{13}		
Y_1	12	-0.2030	-0.3138	-0.2740	0.7288[d]	-0.0197	0.2035	0.7214[d]	0.0119	[f]	X_2 or X_{12}
		X_5	X_1	X_3							
Y_2	24	0.4290[e]	0.7236[d]	0.6265[d]	....	....	....	....	....	0.7710[d]	X_1

[a] Dependent variables: Y = average infiltration rate last 20 minutes, inches/hour; Y_1 = time before the start of runoff, minutes; Y_2 = time from start of runoff to stability, minutes.

[b] Independent variables: X_1 = dry weight of live herbage, grams; X_2 = dry weight of dead materials (litter), grams; X_3 = density of perennial grasses and sedges, per cent; X_4 = bare soil area, per cent; X_5 = slope, per cent; X_6 = soil depth to C horizon, inches; X_7 = range forage condition index, number; X_8 = total soil porosity (3-7 inch and 7+ inch depths), grams; X_9 = water loss at 50 cm tension (3-7 inch and 7+ inch depths), grams; X_{10} = percolation rate (3-7 inch and 7+ inch depths), inches/hour; X_{11} = bulk density (3-7 inch and 7+ inch depths), ratio; X_{12} = litter by weight of total of live and dead materials, per cent; X_{13} = water loss at 90 cm tension (0-2 inch depth), per cent; X_{14} = clay in 0-2 inch depth, per cent; X_{15} = clay in 3-7 inch depth, per cent.

[c] Independent variable significant to one per cent level in regression equation.

[d] Significant to one per cent level; blank = not significant.

[e] Significant to five per cent level.

[f] X_2 and X_{12} are the same independent variables expressed differently. No multiple correlation coefficient calculated because of non-significant values of remaining independent variables.

velopment of a unit hydrograph from watersheds of similar plant-soil complexes. Such an analysis supports the contention that good vegetation slows down the runoff from cloudburst storms, but does not necessarily change the volume of runoff which might be expected.

Examination of infiltration curves of other plant-soil complexes showed a variation in the time that runoff started and in the time for the f_c to become constant. Observations of timber-grass and aspen-litter stands on soils derived from granite both showed a longer period before runoff started as well as a longer period to reach stability when compared to a grassland on the same soil.

The infiltration curves of a grassland on granite-derived soils varied according to the condition of the grass vegetation. Under "good conditions" (grasslands with an abundance of desirable grass growth, usually bunchgrasses) the time before runoff started was long (three to eight minutes) and the time to level off at the f_c delayed (20 to 30 minutes). Often the f_c remained high. Under "poor conditions" (grasslands with a sparse grass growth and many weeds) the time before the start of runoff was short (one to five minutes), and the delaying period before the f_c was reached was also limited (10 to 20 minutes).

Cloudburst storms (total volume of 2.5 inches) in the Colorado Front Range, where the infiltration studies have been carried out, have their peak intensities after the first 20 minutes and before the 50-minute period of the storm. Lesser storms contain their highest intensity during the early part of the storm period, usually before 20 minutes.

The longer the period before the start of runoff when high infiltration rates prevail, the less will be the runoff (rainfall excess) from a particular cloudburst storm. Likewise, the longer the period from the start of runoff to the time when the f_c has leveled off, the less the runoff from the cloudburst.

For the most part, these two delaying actions increase surface detention storage and occur where native vegetation and litter are most abundant. On areas of sparse vegetation the delaying action is limited and surface detention is small.

The f_c of areas with abundant vegetation and those of sparse vegetation may be equal or different, depending upon the character of the soil surface and the presence or absence of restrictive layers (clays) in the subsurface. In some measure abundant vegetation affects the magnitude of the f_c through indirect means such as root holes, aggregation, and by protecting the pores of the soil surface from sealing. Generally, however, the f_c is dominated by soil texture and structure.

Analyses are continuing along these lines to determine whether the f_c is the best measure on which to base comparisons between different plant-soil complexes. Infiltration studies in western Colorado have been conducted in different vegetation types existing on sandstones, shales, andesite, and rhyolite soils and under different intensities of grazing use. At the Manitou Experimental Forest, an infiltration study has been under way for the past ten years to determine the effect of different grazing intensities on grassland, timber-grass, and timber-litter cover types occurring on soils derived from granitic alluvium. Until a base for comparison is well established, the significance of the grazing treatments on infiltration cannot be tested.

L. L. Harrold (U. S. Soil Conservation Service Research, Coshocton, Ohio)--Watershed studies on the Coshocton hydrologic Experiment Station in 1952 revealed the effectiveness of land-surface conditions on infiltration capacity rates on cornland. On poor-practice cornfields where erosion losses have been large, infiltration rates during natural storms are low. On conservation-practice watersheds, the infiltration rates are about 30 pct greater. On mulch-corn watersheds infiltration rates are more than 100 pct greater.

On a corn watershed where the surface soil was treated with a chemical conditioner (Krilium) the infiltration rates were slightly higher than those for the mulch corn watershed. On this area, the effect of the chemical conditioner was also evident in the increase of the rate of water transmission to lower depths. This characteristic should be reflected in maintaining infiltration rates at high levels for a longer time.

All the above infiltration values were obtained from the hydrograph analysis of small watershed records. A small amount of work is being done on the use of infiltration curves thus derived to develop runoff amounts and rates for larger, mixed-crop watersheds. Much more needs to be done along these lines.

Leon Lassen, Howard W. Lull, and Bernard Frank (U. S. Forest Service, Washington, D. C.)--In Circular No. 910 of the U. S. Department of Agriculture, there is presented a simplified, but comprehensive, description of plant-soil-water relations in watershed management. Factors affecting soil porosity along with infiltration and percolation are discussed and illustrated.

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U. S. Soil Conservation Service (L.L.H.),
Coshocton, Ohio

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Transactions, American Geophysical Union Volume 34, Number 5 October 1953

PROGRESS REPORT, SEISMOLOGICAL LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, 1952

H. Benioff, B. Gutenberg, and C. F. Richter

(Contribution No. 622, Division of the Earth Sciences, California Institute of Technology, Pasadena, California)

Station development

Changes in seismograph installations during the year were as follows:

Barrett, located at 32°40.8′ N, 116°40.3′ W, h = 510 m, was installed as temporary station on January 17, 1952, with short-period Benioff Z (vertical-component instrument). It is to be equipped as a permanent station in 1953.

Santa Barbara installation was modified on March 11, 1952, to record on film with short-period Benioff Z and short-period torsions N and E.

La Jolla station was discontinued on July 30, 1952.

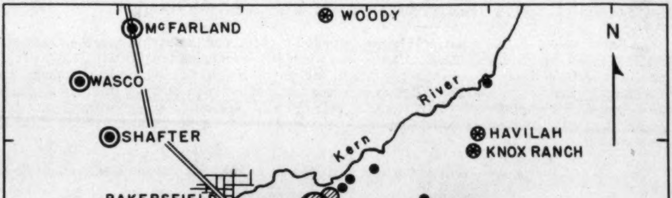
WOODY
McFARLAND
N
WASCO
Kern River
SHAFTER
HAVILAH
KNOX RANCH
BAKERSFIELD
KING RANCH 15 MILES
ARVIN
WHITE WOLF FAULT
TEHACHAPI
TAFT
MARICOPA
WHEELER RIDGE
MOJAVE
GARLOCK FAULT
SAN ANDREAS FAULT
FORT TEJON
0 5 10 15 MI.
0 10 20 KM.
LEBEC
MARCH, 1953
CHUCHUPATE
SPECIAL STATIONS

Fig. 1--Map of Kern County area showing active faults, stations, epicenters of shocks with magnitude 5 or more (circles), and available tentative epicenters of shocks with magnitude 4 to 4.9 crosses)

The following recording units were installed in consequence of the Kern County earthquakes beginning July 21, 1952, all with short-period Benioff Z (see Fig. 1): First unit was located at Chuchupate, July 21 to November 19; at Fort Tejon, November 21 to date (January, 1953). Second unit was located at Havilah, August 5 to September 4; at Knox Ranch, September 4 to November 10; at Williams Ranch, November 11 to date. Third unit was located at Woody, August 5 to date. This installation is being equipped as a permanent station. Fourth unit was located at King Ranch, October 16 to date. These locations are as shown in Table 1.

Table 1--Location of stations

Coordinates	Latitude N	Longitude W	Elevation (h)
	° ′	° ′	m
Chuchupate	34 48.5	119 00.7	1590
Fort Tejon	34 52.4	118 53.7	980
Havilah	35 30.6	118 31.0	990
Knox Ranch	35 29.0	118 31.7	1090
Williams Ranch	35 17.9	118 36.7	430
Woody	35 42.0	118 50.6	500
King Ranch	35 19.7	119 44.7	760

Kern County, California, earthquakes

A portable seismograph began recording not far from Tehachapi within seven hours after the principal earthquake. In the following weeks portable instruments were operated at 12 localities in Kern County; individual runs lasted from a few hours to a few days.

On September 3-5, 1952, portable units recorded at three points surrounding the northern portion of the disturbed area. Small aftershocks were still occurring frequently; many were recorded at short distances by these three units in addition to that at Havilah or Knox Ranch. Among these shocks were several large enough to be recorded at the distant stations of the network. These data alone are sufficient for revision of seismic wave velocities and investigation of crustal structure; this research is going forward, integrated with the general investigation of the Kern County shocks.

Two portable units were sent to the southern part of the disturbed area on November 12-13, 1952.

The supplementary portable units record on the Benioff hot stylus recorder with a capacity transducer seismometer. This has the great advantage of visible recording, which provides information for immediate use under emergency conditions, and also is less easily ruined by accidents such as are apt to occur with photographic recording in the field. However, it has been operated only where power supply was available.

The best determination thus far available for the main shock is as follows: epicenter 35°00′ N, 119°02′ W, origin time 11h 52m 14.3s July 21, 1952, GCT, magnitude about 7.7. The 21 aftershocks of magnitude 5 and over have been worked out as shown in Figure 1. No aftershocks of estimated magnitudes 5.0 or greater have occurred since the end of August. Aftershocks of magnitude 4.0 to 4.9 continue with decreasing frequency. About 170 of these occurred before, the end of August, 14 in September, 9 in October, 8 in November, and 6 in December, 1952. The smaller the shocks the more numerous they are; as an example, about 80 of magnitude 3.0 to 3.9 occurred in September alone. About September 1, the daily average of all shocks countable on the seismograms at Pasadena was near 40; the special stations operating at shorter distances regularly recorded far more. Immediately following the main shock, sensitive instruments at distances as much as 200 mi showed continuous ground motion for about 36 h.

Investigation is being directed under C. F. Richter to the aftershocks of magnitude 4 and over to determine their geographical distribution in relation to their time sequence. For the first eight hours this is difficult because of overlapping traces of successive shocks. About 100 subsequent shocks of this class are available for study; of these about 40 have been investigated in detail at this writing. G. G. Shor has placed the remainder approximately, using the differences in times of arrival of first motion at the several stations.

The large aftershock at 00h 38m July 23, 1952, GCT, marks a definite change in the pattern of activity. Previous to this, the epicenters of all located shocks of the series follow the general trend of the White Wolf Fault, from the epicenter of the main earthquake near Wheeler Ridge northeast to a point east of Caliente. Most of these epicenters are some miles away from the surface fault trace and southeast of it, indicating dip of the fault surface in that direction. A few shocks, apparently shallower, are closer to the fault trace; but none in this first epoch is across the trace on its northwest side.

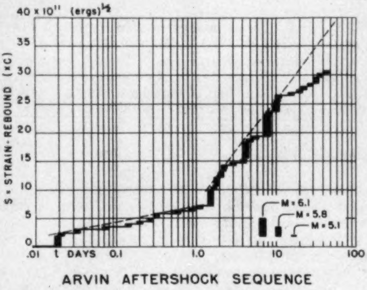

Fig. 2--Elastic strain rebound characteristic of Arvin aftershock sequence, based on preliminary magnitudes

The large aftershock of July 23, on the other hand, was definitely northwest of the White Wolf Fault. Many of the subsequent shocks were so located, although others continued to occur on the southeast side.

The elastic-strain rebound characteristic (Fig. 2) derived from the preliminary magnitude estimations indicates that the strain energy which generated the major earthquake was principally of compressional type. The beginning of the second phase, 36.7 h after the principal shock, coincides with the change in pattern of activity just mentioned and is marked by the first aftershock of any magnitude so far located on the north side.

Two large shocks of July 25, east of Caliente, constitute a new event. Although clearly in line with the White Wolf Fault, these were much larger than any previous aftershocks as far northeast along that line. The series from this particular epicenter includes a foreshock on July 25 and a long series of aftershocks, some of them of magnitude 5 or over.

A large shock on July 29, much farther west, also had a foreshock, and a series of aftershocks whose epicenters align roughly parallel to the White Wolf Fault; this includes a shock on August 22, which though smaller was much more damaging at Bakersfield.

Minor shocks have apparently occurred scattered over an area much wider than that including the shocks of magnitude 4 and over; but toward the end of 1952 an increasing fraction of aftershocks was occurring at points remote from the White Wolf Fault.

Depths of most of the larger shocks appear to be near the usual depth for the region, which is taken to be about 16 km (10 mi). A few are shallower, and at least one (that on July 31) is deeper (depth tentatively 25 km). The principal earthquake of July 21, and the aftershock near Bakersfield on August 22, are among those provisionally assigned to the usual depth.

The instrumental hypocenter for the principal earthquake indicates the point at which faulting was initiated. The geographic pattern of the larger aftershock epicenters (Fig. 1) suggests that the faulting then extended northeastward approximately 40 mi to a point beyond Caliente. Since there are several well-authenticated cases in which faulting began at one end of an active segment, we do not consider this phenomenon unusual. The only known foreshock of the principal earthquake occurred on July 21 at 09h 43m GCT, with an epicenter slightly farther west, and magnitude 3.1.

At all the nearer stations the initial motion of the principal shock is toward the epicenter which, considering the distances involved, is consistent with reverse faulting. The relatively small displacement of the epicenters from the surface trace of the White Wolf Fault, together with the probable depths of origin, indicates a fault surface having a dip of well over 45°.

The delay of Pn attributed to the "root of the Sierra Nevada" is confirmed beyond reasonable doubt, since in many of the aftershocks the epicenters are well surrounded by nearby stations so that origin times are accurate within better than one second. The delays in Pn increase in general as the epicenters approach or enter the Sierra Nevada to the east. In the main shock the delay of the first waves relative to the times along other paths was about four seconds at Reno (most of the path under the Sierra Nevada), and about three seconds to Tinemaha or Haiwee.

Bryson earthquakes

On November 22, 1952, at 07h 46m 38s GCT (November 21, 23h 46m 38s PST), an earthquake of magnitude 6+ originated near 35° 50′ N, 121° 10′ W. This is not a part of the Kern County series; it was followed by numerous aftershocks from about the same epicenter. Field investigation by D. Leeds of the U. S. Coast and Geodetic Survey and G. G. Shor indicated minor damage (intensity 7+) in the vicinity of Bryson, a small community east of the instrumentally located epicenter.

Corona blast

On July 26, 1952, another major blast was fired at the Corona quarry of the Minnesota Mining and Manufacturing Co. This was also timed at the source with the kind cooperation of company officials. Preparations had been made to record this blast at a series of distant stations. This was done on a slightly reduced scale, since some of the equipment and personnel were engaged in recording the aftershocks of the earthquake of July 21. One of these aftershocks took place about one minute before the blast was fired on July 26, and interfered with the recording at distant locations.

Instrumental development by Benioff

Capacity transducer seismograph--The development mentioned in the preceding report has continued. The crystal oscillator has been changed from a one-tube circuit to a two-tube circuit in which the crystal is operated at series resonance between the cathodes of the two tubes. This has improved the amplitude stability so that the gas voltage regulators on the anode supply circuit have been eliminated. Although the vertical component seismometer was constructed with an elinvar-type alloy spring, it exhibited sufficient temperature responsiveness to require fairly frequent adjustment. This difficulty has been satisfactorily overcome by the use of a one-stage amplifier stabilizer circuit in which the output is fed into the seismometer damping coil. The circuit is, in effect, a Miller integrator with a time-constant of approximately 20 min. Thus for pendulum movements with periods substantially less than 20 min the automatic balancing effect is negligible, but for long-period disturbances the electrical restoring force is fully effective. This modification has eliminated the need for periodic adjustment.

Hot stylus recorder--Two forms of hot stylus recorders using Sanborn heat sensitive paper have been developed to the point of satisfactory operation. In the first, a four-foot length of ten-inch wide paper is cemented at the ends to form a continuous ribbon which is driven over a sharp edge at one mm/sec. A standard Sanborn galvanometer hot stylus engages the paper over the sharp edge and produces a record without writing-arm curvature. In the other form the paper is wrapped around a standard seismograph drum and the galvanometer is supplied with a specially constructed stylus. In this form, writing-arm curvature is not eliminated but the recorded line is very much improved and approaches closely the quality of a photographic line. Moreover, the disadvantage of the closed loop recording paper is eliminated.

Long-period strain seismograph

The sensitivity of the routine 70-sec long-period strain seismographs at the Laboratory has been raised to the point that during the first hour or two of a large teleseismic recording the amplitudes are too large to be satisfactorily recorded. In order to avoid this, a second recorder of approximately 1/20 the sensitivity was set up using a writing speed of 7 1/2 mm/min. Moreover, with the reduced sensitivity it was possible to use a galvanometer of longer period, approximately three minutes. The resulting seismograms are very striking. In the Kamchatka earthquake of November 4, a wave of over one-minute period was recorded for PP. The largest amplitude was written by a G_1 impulse of approximately 60-sec period. This was followed by a mantle Rayleigh wave impulse R_1 of approximately 70-sec period. G_2, G_3, G_4, and G_5 were also recorded with periods extending up to 7.9 min. The mantle Rayleigh waves R_2, R_3, R_4, and R_5 are also clearly recorded with periods up to about eight minutes. Two unidentified wave groups having transmission times corresponding with $P'R_1$ and $P'R_2$ were also recorded.

Tape-recorder playback

A Fairchild oscillograph recorder was purchased for transcribing the tape records to conventional seismograms recorded on 35-mm film. The recorder has provision for adjusting the film speed to any desired value. By operation at a film speed of 30 in/sec with a playback tape speed of 15 in/sec the resulting transcription is equivalent to a directly recorded seismogram of

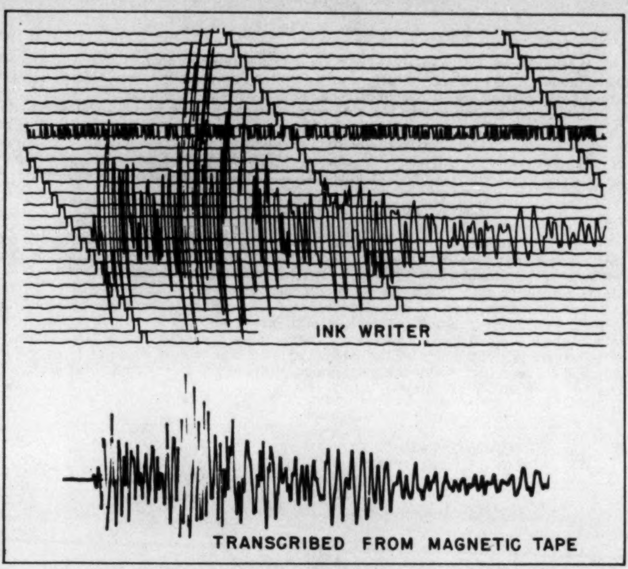

Fig. 3--Vertical-capacity seismometer recordings of Kern County aftershocks, Aug. 30, 1952, 04h 56m 21.4s GCT, M = 5.0, $\Delta = 125 \pm$ km

one mm/sec. In Figure 3 a copy of a transcribed seismogram is shown together with the corresponding record written with the ink recorder. Except for a reversal of phase, the two are very nearly identical. The small difference is due to the response characteristic of the 0.15-second period ink writing galvanometer and to a small residual equalization requirement of the tape-recorder assembly which has not yet been introduced.

Project sponsored by the Geophysical Research Division
of the Air Force Cambridge Research Center

Instrumentation--Work on the installation of quartz tubes for the indicating arms of the two strain seismographs has been completed and preliminary recording is now in progress. A well has been constructed for housing the third of the variable reluctance vertical seismometers of a tripartite network. The other two seismometers are located in the recording building and strain seismograph well respectively. Laying of the cable for the third instrument is also complete. A revised triple galvanometer recorder is being constructed. The first recordings made with the two strain instruments frequently exhibit parallel phase traces indicating Rayleigh wave types, and occasionally phase opposition traces occur which are characteristic of Love-type waves. In general, we may expect simultaneous arrival of waves from more than one source and of both Rayleigh and Love types with corresponding complexity of the seismogram. The amplitudes are at present too large for use of the maximum available sensitivity.

Study of microseisms--A study was carried on by Gutenberg of microseisms recorded at several Pacific Coast stations extending from Mexico City on the south to Victoria, B. C., on the north. Comparison of the recorded microseismic amplitudes with amplitudes of ocean waves measured at three points along the Southern California coast showed strong correlation. However, relatively long microseimic periods often occurred simultaneously with relatively short periods of the ocean waves.

Low-velocity layer at about 15-km depth

Further evidence for the existence of a low-velocity layer at approximately 15-km depth has been studied by Gutenberg. If foci occur within the low-velocity layer, a relatively large fraction of the radiated energy should be confined to the channel. In order to rise to the surface by ordinary propagation other than diffraction or scattering, waves propagated downward must reach a depth at which the wave velocity is at least as great as the maximum velocity above the channel. Such waves should have a travel-time curve with an apparent velocity approximately equal to the maximum velocity above the channel. This travel-time curve may be misinterpreted as representing waves refracted at a non-existent discontinuity below the channel.

Low-velocity layer at a depth of about 100 km

New evidence for the low-velocity layer at a depth of about 100 km was found by Gutenberg. He used the apparent wave velocities of P and S near the individual points of inflection of their travel-time curves in more than 70 deep-focus earthquakes (focal depths 60 to 600 km) to calculate the respective velocities at the depth of focus. The velocities clearly decrease below the Mohorovicic discontinuity with a minimum at a depth of roughly 100 km for longitudinal waves and 150 km for transverse waves. Poisson's ratio increases from about 0.26 at a depth of 50 km to 0.29 at 250 km and does not change noticeably in the deeper portion of the Earth's mantle. There is no evidence of a discontinuity in the mantle between the low-velocity layer and a depth of about 950 km nor of noticeable differences in velocity at any given depth between the various regions for which data are available.

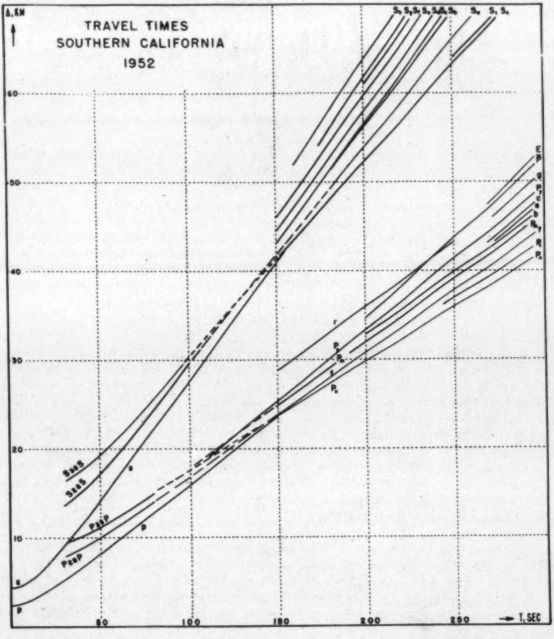

Fig. 4--Revised normal travel-time curves for Southern California

Travel-time curves for local shocks in Southern California

G. G. Shor has constructed average travel-time curves for local earthquakes in Southern California on the basis of various recent papers by Gutenberg. The essential portion is reproduced in Figure 4.

Investigation of waves through the core

A detailed study of SKS was carried out by R. Nelson as a doctoral thesis.

Routine observations of local and distant earthquakes

This program continues under the supervision of C. F. Richter. There were three great earthquakes during 1952: on March 4, magnitude 8.3, in Japan; on March 19, magnitude 7 3/4, in the Philippines; and on November 4, magnitude 8 1/4, in Kamchatka.

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DISCUSSION OF

"NUMERICAL ANALYSIS OF CONTINUOUS UNSTEADY FLOW IN OPEN CHANNELS"

by PIN-NAM LIN

[Trans., v. 33, pp. 226-234, 1952]

J. C. Schönfeld (Central Research Division, Directorate General of the Rijkswaterstaat, The Hague, The Netherlands)--The paper presents a useful contribution to the application of the theory of characteristics to the propagation of long waves under influence of frictional resistance, a subject to which the present writer's thesis [Propagation of tides and similar waves, Staatsdrukkerij, The Hague, 232 pp., 1951] was likewise devoted. It may be interesting to compare the author's new method to other methods, and to define more exactly the field of application of the new method. We first give a brief description of the methods to which we shall compare the author's new method.

In the first place we have the method of Craya and the first method of the present writer [see Thesis, chap. 8] with continuous characteristics and, if necessary, operated by trial-and-error (or rather iterative) processes. In the present writer's first method, which is essentially the same as Craya's method, although differing in various details, the solution is constructed for the characteristic variables $f^+ = \sqrt{gy} + v/2$ and $f^- = \sqrt{gy} - v/2$ (y = depth; v = velocity of flow). Along lines

$$dx/dt = c^+ = v + \sqrt{gy} \quad \text{or} \quad dx/dt = c^- = v - \sqrt{gy}$$

(characteristics), we have

$$df^+/dt = - a^+ = - (g|v|v)/(2C^2 y) \text{ respectively } df^-/dt = - a^- = (g|v|v)/(2C^2 y)$$

Pairs of values of f^+ and f^- are found each time by constructing two characteristics. The construction consists of drawing one projection of the characteristic in a tx-diagram (slope c^+ or c^-), and another projection in a diagram of tf^+ or tf^- (slope a^+ or a^-). The quantities c^+ and a^+ or c^- and a^- are defined from estimated averages of f^+ and f^-; instead of being computed, they may be found by means of a nomogram [see Thesis, chap. 14, par. 21]. The estimations for f^+ and f^- should be checked after the execution of the two constructions, and, if necessary, the constructions are repeated with better estimations (iteration; trial and error).

A second method was developed by the present writer [see Thesis, chap. 12, par. 23] for application in irregularly shaped channels. The channel is schematized by a division in rather short sections. Distinction is made between the width of the stream bed, b_s, and the width of the water surface, b, which are both considered as functions of the height of the water level above datum h. Across a transition of one section to another section with a different area of cross section A, the velocity of flow v and the water level h vary suddenly. The discharge Q, on the other hand, varies continuously across the transition, and the energy head above datum H does likewise, or very nearly so. Therefore, the characteristics are constructed in a diagram of HQ, together with a tx-diagram, in a way similar to Craya's method.

The construction of a characteristic is based on estimated average values $\overline{Q}$ and $\overline{h}$ of Q and h. The subcharacteristics (projections of the characteristics in the tx-plane) are defined by

$$dx/dt = c^+ = \gamma \overline{Q} + c_o \quad \text{and} \quad dx/dt = c^- = \gamma \overline{Q} - c_o$$

where $\gamma = (b + b_s)/(2bA)$ and $c_o = \sqrt{g A/b}$ are treated as given functions of the average water level h. Although the estimation of the averages requires a check, the construction of the subcharacteristics is seldom obstructed by trial and error.

The construction of the contra-subcharacteristic (projection in the HQ-plane) follows the equations

$$\Delta H = - W|Q_1|Q_1 - Z\Delta Q \text{ respectively } \Delta H = W|Q_1|Q_1 + Z\Delta Q$$

where Q_1 is the (known) value of Q at the beginning of the characteristic, and

$$Z = Z_o - \zeta \overline{Q} + W|\overline{Q}| \text{ respectively } Z = Z_o + \zeta \overline{Q} + W|\overline{Q}|$$

whereas

$$Z_o = 1/\sqrt{gAb},\ \zeta = (b - b_s)/2gb\,A^2, \text{ and } W = \Delta x/(C^2A^3/b_s)$$

(Δx = length of channel section) are treated as given functions of $\overline{h}$. In these formulas the resistance has been reduced in such a way that the construction becomes very insensitive to errors in the estimation of $\overline{Q}$. This eliminates trial-and-error processes nearly entirely.

Although not quite essential, the method is preferably executed in fixed sections, and the characteristics are defined in such a way that their intersections correspond to the transitions between the sections. This means that the characteristics are not continuous; in this aspect the method agrees with the author's new method. The difference between the two methods lies in the fact that the author operates with constant Δt, while the present writer operates with fixed Δx.

The discontinuities in the characteristics are overcome by inter- or extrapolations in Ht- and Qt-diagrams; these diagrams are useful recapitulations of the calculation, moreover.

Summarizing, we have three types of method: (1) methods with continuous characteristics (Craya's method, present writer's first method); (2) method with constant Δt (author's new method); and (3) method with fixed Δx (present writer's second method).

The fields of application of the above methods can be separated by considering two criteria. In the first place we may distinguish between regularly and irregularly shaped channels, and in the second place between rapidly varying motions (relatively short waves) where the inertia is predominant, and slowly varying motions (relatively long waves) where the resistance is predominant.

In opposition to the methods with constant Δt and with fixed Δx, the methods with continuous characteristics can avoid inter- or extrapolations. This means less work, and the elimination of a source of inaccuracies. Moreover, the operation is very simple. In the present writer's first method all computations are reduced to one adjustment in one nomogram.

It is therefore clear that the methods with continuous characteristics are preferable as long as they are well applicable.

According to the present writer's experience, trial and error usually becomes obstructive when the resistance dominates the inertia. In case of a dominating inertia (and not too long steps along the characteristics) a skilled computer can at once estimate the required averages with sufficient accuracy.

Most natural conduits like rivers and estuaries, and some artificial canals as well, are of such an irregular shape that a schematization by a prism is rather crude. The schematization of such an irregular channel by rather short sections, distinction between b_s and b, and treatment of b_s and b as functions of the height of the water level, has proved itself justified in a long experience in Holland in connection with harmonic, iterative (power series) and characteristic methods.

Hence we conclude that the methods with continuous characteristics (Craya's method, the present writer's first method) are preferable in case of regularly shaped canals, and rapidly varying motions (predominant inertia).

The author's new method with constant Δt will become superior when, in regularly shaped canals, the resistance becomes predominant (slowly varying motion). A competitive method in this case may perhaps be obtained by a modification of Craya's method in such a way that the resistance is treated in a manner similar to the present writer's second method.

In irregularly shaped channels and channel networks the present writer's second method should be applied.

Pin-Nam Lin (Department of Civil Engineering, Colorado A. and M. College, Fort Collins, Colorado, Author's closure)--The method proposed by the writer consists mainly in the use of a constant time interval and an independent set of characteristics in each step of computation. As previously indicated on page 228 of the paper, the reason for using constant Δt is to eliminate the trial process arising from the presence of the resistance terms. When the resistance is assumed to be negligible, one has a relatively simple case that can be solved in a straightforward manner, and hence does not need special treatment. The use of constant Δt for this case is therefore basically unnecessary. The use of an independent set of characteristics in each step, that is, the use of "discontinuous" characteristics, provides greater solvency in planning the computation, in order that computed points can be so distributed as to best define the shape of the integral surface. To follow the procedure of keeping Δt constant, one must work with "discontinuous" characteristics. The converse, however, is not true. In this connection, the reader may find an example of the use of "discontinuous" characteristics (prepared by the writer in 1950) of interest [see ROUSE, H., Engineering hydraulics, John Wiley and Sons, pp. 703-707, 1950].

In so far as the very purpose of performing numerical computations is to obtain useful results for practical applications, the writer cannot agree with Schönfeld that "methods with continuous characteristics can avoid inter- or extrapolations," and that "this means less work and the elimination of a source of inaccuracies." The writer, however, is not concerned with extrapolation since he has not used it in his method. With regard to the matter of interpolation, the following comments may be offered.

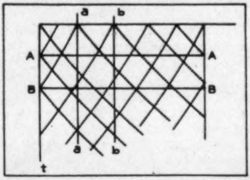

Fig. 11--Flow data as a function of time

There are in general two types of information that are of practical value, namely, the flow data at a given section as a function of time (for instance, data at points on aa, bb of Fig. 11), and those at a certain instant as a function of distance along the channel (for instance, data at points on AA, BB, Fig. 11). In the methods of "continuous" characteristics, flow data are computed only at intersections of characteristics. As a result, such information as just mentioned cannot, in general, be provided without resorting to interpolation. Using the method of "continuous" characteristics, the information would be even more questionable because, for practical reasons, it is likely that interpolation will be based on only two or three adjacent points, whereas, using the method proposed by the writer, results of a step computation are plotted, and the smooth curve giving best fit to the computed points is used in subsequent computation. Thus one can see that in order to provide useful data none of the methods can really avoid interpolation. It will be necessary sooner or later.

In general, the writer does not believe that the error resulting from curve fitting is of significant consequence in open-channel calculations. It is rather the distribution of the computed points that could seriously affect the accuracy of the computations. Thus if salient features such as a peak in the integral surfaces were missed, the resulting error could be unacceptable. Using methods with continuous characteristics, one is by no means sure that the strategic points in the integral surface are included in all stages of computations, as the general location of each characteristic is predetermined by previous computations. If additional characteristics are required to improve the accuracy of computations, then either interpolation has to be used or new characteristics have to be started from the very beginning. This means either the use of a procedure that the methods of "continuous" characteristics are said to avoid or considerable amount of additional work. According to the writer's procedure of using "discontinuous" characteristics, one is free to plan the computations in each step. Consequently, the distribution of the computed points in each step of computation should be the best in the sense that the integral surface could be most accurately defined with minimum number of computed points.

According to the writer's experience, it is the trial process that is the most time-consuming. Such mechanical or routine work as plotting and fitting a curve to the computed points at the conclusion of each step of computation certainly takes little additional time. By using "discontinuous" characteristics and keeping Δt constant as proposed by the writer, trial solution on the U-V plane is eliminated in most cases. Time saved in this manner far exceeds the time required in straightforward plotting and curve fitting. Plotting of results of computations as each step proceeds also offers the opportunity of visual check against gross mistakes.

Both of Schönfeld's methods require trial processes in the solutions on the t-f and H-Q planes. In the first method, the trial process is aided by a nomogram, which is prepared on the basis of the following

$$\begin{cases} dx/dt = c^{+} = V + \sqrt{gy} \\ (d/dt)\,(V/2 + \sqrt{gy}) = df^{+}/dt = -\,(g/2)\,S_f = -\,g|V|V/2\,C^2\,y \end{cases}$$

and

$$\begin{cases} dx/dt = c^{-} = V - \sqrt{gy} \\ (d/dt)\,(V/2 - \sqrt{gy}) = df^{-}/dt = -\,(g/2)\,S_f = -\,g|V|V/2\,C^2\,y \end{cases}$$

where the Chezy coefficient C is defined by a formula in the form of

$$C = \alpha(1 - \beta/\sqrt{gy})$$

A nomogram so constructed can only be used for the calculations of points in the channel. For points along the boundaries, further aid has to be devised.

Schönfeld refers to his second method as a method of fixed Δx. The method as explained in Chapter 12 of his dissertation, however, does not use constant Δx and there is no hint of using "discontinuous characteristics. Schönfeld states that in this method "the resistance has been treated in such a way that construction becomes very insensitive to errors in the estimation of $\overline{Q}$," and that "this eliminates trial-and-error process nearly entirely." Study of the details given in his dissertation impresses the present writer that Schönfeld's treatment of resistance terms seems to be rather arbitrary, and it is difficult for the present writer to see how one can be confident that the treatment will be good in general. According to page 186 of Schönfeld's dissertation, the resistance head loss is expressed as $H_r = \overline{W}|\overline{Q|Q}$, where the bars denote averages over a segment of a characteristic, Q stands for discharge, and $W = \Delta x/C^2A^2R$. Ignoring the variation of C with depth of flow, one can see that W still varies with A^2R which is an unknown and in some cases could be quite sensitive to the change in depth. In the dissertation, it is also stated that "$\overline{W}$, an average value of the coefficient for resistance of the section under consideration, may be defined from $\overline{H}$." This means that the computer would have to estimate the average value of W and then check it later. The quantity $|\overline{Q|Q}$ is arbitrarily written as $|\overline{Q|Q} = \overline{S} = S_m + Q_m\,(Q_2 - Q_1)$. Rules are then given to compute Q_m and S_m. When Q_1 and Q_2 have the same sign, $S_m = |Q_1|Q_1$ and $Q_m = |(2/3)Q_1 + (1/3)Q_2|$. When Q_1 and Q_2 are opposite in sign

$$S_m = -\,\mu\,|Q_2 - Q_1|\,(Q_2 - Q_1) \quad \text{and} \quad Q_m = \lambda\,|Q_2 - Q_1|$$

where $\mu = 1/4 + r^2 - (4/3)\,r^3$ and $\lambda = (1/4) + (r/2) + r^2 - (2/3)\,r^3$, in which

$$r = (Q_1 + Q_2)/2\,(Q_2 - Q_1)$$

The writer wonders how many would prefer to follow all of the foregoing rules without assurance regarding how much and how often the trial process would be reduced.

When the idea of "discontinuous" characteristics is applied, Δx can be kept constant, and the result is the method of fixed Δx proposed by Schönfeld. In this case, however, the solution of the equations of "contra-subcharacteristics" is not direct because there are two distinct values of z existing at every intersection of characteristics. The advantages gained in this procedure will then be principally those associated with the use of "discontinuous" characteristics. When the non-uniform channel can be approximated by fairly long reaches of uniform channels, it appears that the method of constant Δt can be used to advantage. When the reaches are very short, the method of fixed Δx seems very promising.

Although there are points on which the present writer takes a different view, the discussion by Schönfeld is very informative and stimulating. The writer should like to express his sincere thanks to Schönfeld for the fine discussion as well as for the courtesy of lending a copy of his dissertation.

DISCUSSION OF

"THE EFFICIENCY OF DEPTH-INTEGRATING SUSPENDED-SEDIMENT SAMPLING"
by NING CHIEN

[Trans., v. 33, pp. 693-698, 1952]

R. F. Kreiss and **B. R. Colby** (U. S. Geological Survey, Lincoln, Nebr.)--The author has developed equations and approximate curves to express the percentage of the total sediment discharge that is carried in suspension above the lowest point reached by the nozzle of a depth-integrating sediment sampler. He assumes that bed load and suspended load are defined by the equations in a paper by H. A. EINSTEIN [The bed-load function for sediment transportation in open-channel flows, U. S. Dept. Agric., Tech. Bull. 1026, 1950]. The percentage is termed the efficiency of sampling.

In a vertical strip of unit width, the suspended-sediment discharge discussed by the author is in effect the product of the mean concentration of the depth-integrated sample, the water discharge in that portion of the depth above the lowest nozzle position, and a factor for converting the result into desired units, such as tons per day. In contrast, the common operating practice is to compute the suspended-sediment load as the product of the measured concentration, the total water discharge, and the conversion factor. The difference in computed suspended-sediment discharge by the two methods is sometimes appreciable as, for example, in the wide, shallow streams that drain the sandhills of Nebraska.

Fortunately the suspended load, as computed by the practical and usual method, can be converted simply to that of the author by multiplying by the ratio of the lesser to the greater, or total, water discharge. The efficiency for the usual method of computation may be determined by dividing the author's efficiency, Eq. (20) or Figure 2, by the same ratio.

The ratio of water discharge above a point to total water discharge is presented in Figure 3. Each discharge was computed by integrating between appropriate limits the approximate velocity curve

$$u_y = 5.75\, u_*'\, \log_{10}\,(30.2\, y/\Delta)\ \ldots\ldots\ldots\ldots \quad (21)$$

which may be obtained by dividing the author's (6) by (1). The curve in Figure 3 was determined for P = 10 but is correct within two per cent for values of P, (10), between 9 and 12.

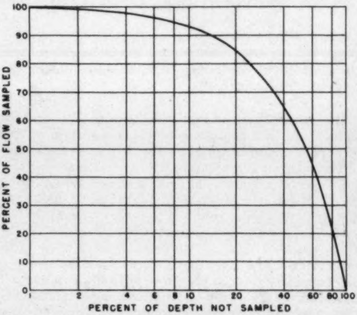

Fig. 3--Ratio of water discharge above a given point to total discharge, P = 10

Two other items from the author's paper seem to require comment. In Table 1, the lowest point of the body of the US DH-48 depth-integrating sampler is said to be 2 5/8 inches below the nozzle. This statement is correct but misleading. When a sampling bottle (pint milk bottle) is inserted in the body, the lowest point of the bottle is about 0.3 ft below the nozzle. Hence, α preferably should have been taken as 0.3 ft or more for the example of Figure 2, instead of three inches.

The other item pertains to the determination of z. Determination of z by field measurements is preferred to computation by (2). In common with many observations elsewhere, the observations of z for streams that are sampled by the U. S. Geological Survey in the Missouri River basin are almost always smaller than those computed by (2).

When point-integrated samples in a vertical are not available for determining z by (1), the depth-integrated samples can be used. For each size fraction other than wash load, only one value of z can yield both (a) a concentration at the bed layer equal to that determined from the bed-load transport determined according to the method of Einstein, and (b) a mean concentration in the range of depth above the lowest sampling point equal to the concentration of the depth-integrated sample. The size range for which z is thus determined should be a significant fraction of the bed-load discharge and of the suspended-sediment discharge as well. For other size ranges, z can be computed in proportion to the settling velocities of the sediments. Computation of z from either point-integrated or depth-integrated samples is preferred to computation by (2).

Ning Chien (Fluid Mechanics Laboratory, University of California, Berkeley, Calif., Author's closure)--Kreiss and Colby have generously added to the practical value of the original paper by pointing out the necessity of modifying the efficiency by a discharge factor which may be quite important for wide, shallow streams. Figure 3 should prove to be very satisfactory in practical use; although, strictly speaking, the percentage of flow sampled is a function of the bed roughness also.

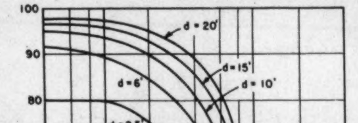

Fig. 4--Efficiency of the depth-integrating suspended-sediment sampling expressed in terms of the total sediment discharge for α = six inches

Figure 2 was constructed merely for illustrative purposes. While using the author's method to determine the total load from suspended-sediment sampling, the value α should always be determined according to the sampler used and the sampling method adopted in the field. A set of curves similar to Figure 2 can then be constructed based on (20) for that particular α value, and used henceforth in the analysis. Since the construction of these curves is quite laborious, the author has prepared another set of curves for α = six inches in Figure 4. The efficiencies for other values of α can be obtained from Figures 2 and 4 with proper interpolations. A comparison of Figures 2 and 4 also serves to indicate the importance of measuring the α value accurately, especially for small values of z and d.

The author fully agrees with Kreiss and Colby that if field-measurement data permit the determination of z, this measured z is preferably used instead of the z calculated by (2). Some attempts have been made recently, with some success, at the University of California [H. A. EINSTEIN and NING CHIEN, Second approximation to the solution of the suspended-load theory, Missouri River Div., Corps of Engineers, Omaha, Nebraska, in press] to correlate the measured z and the calculated z by an analytical approach.

The method developed in the original paper also can be used to check bed-load measurements. The conventional box-type bed-load sampler samples a stream of bed load moving along the bed with a thickness of β; here β is the height of the rectangular entrance frame of the sampler which is two inches for a sampler recently used by the author. The rate of sediment sampled by the sampler per unit width, $i_{B\beta} q_{B\beta}$, is related to the total load moving through the river section per unit width, $i_T q_T$, by

$$i_{B\beta} q_{B\beta} = i_T q_T - i_{s\beta} q_{s\beta} = i_T q_T [1 - \{ (2D/\beta)^{z-1} [(d-\beta)/(d-2D)]^z (PI_{1\beta} + I_{2\beta}) \} / (1 + PI_1 + I_2)] \quad (22)$$

where the total load, $i_T q_T$, can be calculated according to Einstein bed-load function.

Transactions, American Geophysical Union Volume 34, Number 5 October 1953

LETTERS TO THE EDITOR

A BIBLIOGRAPHY ON SNOW, ICE, AND PERMAFROST

The Technical Information Division, Library of Congress, under an agreement with the Snow, Ice, and Permafrost Research Establishment (SIPRE), Corps of Engineers, U. S. Army, is preparing a continuing bibliography with abstracts on the basic properties and applications of snow, ice, and perennially and seasonally frozen ground.

The basic guide used in selecting material for inclusion in the bibliography is given in Table 1. Occasionally, articles on such topics as turbulence, crystallography, or micrometeorology are included where an actual or potential relationship to the principal subjects is thought to exist.

Table 1--Guide for selecting material

Snow	Ice	Frozen ground
(a) Physical properties	(a) Physical properties	(a) Physical properties
(b) Metamorphism	(b) Mechanics	(b) Mechanics
(c) Mechanics	(c) Phase changes	(c) Distribution
(d) Removal and control	(d) Removal and control	(d) Construction
(e) Compaction	(e) Trafficability	(e) Theory of frost action
(f) Construction material	(f) Glaciology	(f) Frost-action effects
(g) Trafficability	(g) Freeze- and break-up time of inland waters	(g) Heat and moisture flow
(h) Avalanche studies	(h) Military applications	(h) Military applications
(i) Snow-cover distribution		
(j) Military applications		

It is hoped that all existing technical information on these subjects published since 1930 will be covered. Investigations reported prior to 1930 are not included unless the work is considered basic or very comprehensive. Priority for abstracting is given to current material. Figure 1 illustrates the distribution of the time of publication of the reports abstracted to date. Abstracts have been made from works published in 16 languages. The distribution of the abstracted literature by languages to date is given in Figure 2.

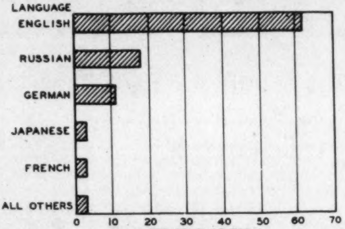

Fig. 1--Time of publication of abstracted literature

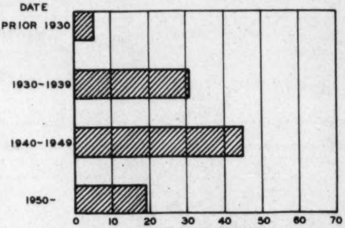

Fig. 2--Language of abstracted literature

Periodical literature is the primary source for material in the bibliography. Approximately 200 journals which have been found to contain pertinent material are regularly searched. Indexes, abstracting journals, bibliographies, and individual references are systematically covered to locate earlier published materials. Theses and dissertations, government documents, report literature, and published patents are also regularly searched. Unpublished data such as mimeographed reports are obtained by personal contacts at scientific meetings and through solicitation of individuals known to be active in associated fields of interest. It is in this area of unpublished material and for references to material receiving limited distribution that the project relies heavily on voluntary contributions from researchers and other interested persons. Material loaned to the project is promptly abstracted and returned. Material furnished for retention is placed on file in SIPRE headquarters and made available for circulation through their library.

The abstracts are intended to be informative rather than descriptive. An attempt is made to include sufficient factual information to enable the investigator to evaluate the original article with reference to his own work.

Abstracts are printed on three- by five-inch cards with appropriate descriptive and subject cataloging. Subject headings are assigned to each abstract on the basis of the principal content of the original item. To date, over 1500 different headings have been used in the bibliography enabling precise location of the material through subject content. The location of the original publication and, when possible, the Library of Congress call number are included. A translated title is included for foreign language articles as well as information on illustrations, tables, appendices, etc., and the number of references. These cards covering both classified and unclassified material are published weekly for authorized users. Unclassified abstracts are also published semiannually in a bound volume as SIPRE Report 12. Each volume contains its own subject and author index. A cumulative subject index will be included in Volume 4.

Over 5000 abstracts have been prepared and current production averages 85 abstracts per week. Three volumes of Report 12 containing the first 4000 abstracts have been published, and it is expected that future volumes will each contain 1500-2000 abstracts. The complete list of subject headings used by the bibliography project is periodically revised and published.

Under current policy, distribution of SIPRE publications is limited to government agencies and government research contractors. Inquiries concerning the availability of these publications should be directed to the Snow, Ice, and Permafrost Research Establishment, 1215 Washington Avenue, Wilmette, Illinois.

John Sherrod, Jr.

Technical Information Division,
Library of Congress,
Washington 25, D. C.

(Received April 10, 1953; presented at the Thirty-Fourth Annual Meeting,
Washington, D. C., May 5, 1953.)

FURTHER DISCUSSION OF

"ON THE ORIGIN OF RIVER MEANDERS"

by P. WILHELM WERNER

[Trans., v. 32, pp. 898-902, 1951, and v. 33, pp. 771-774, 1953]

The Central Board of Irrigation, India, in 1942 [INGLIS, 1942, 1947] differentiated meanders from bends: "A meandering river follows a sinuous path due to natural physical causes not imposed by external restraint," whereas a bend results from external restraint.

Meanders develop naturally where the charge of sediment slightly exceeds what the discharge can carry forward, due, it appears, to the flow then being able to carry an increased charge; but if the charge is considerably greater than can be carried in straight flow, no meander develops until the slope increases sufficiently to transport the charge. Working on this assumption a straight channel was laid in which the gradient varied from steep at the upper end to flat at the lower end, the assumption being that there must be a point at which the discharge and charge would produce meanders. This assumption was tested at Poona early in 1940, and the anticipated meanders resulted.

Where the relationship of slope discharge to charge is not quite right, meanders can still be induced by directing entry flow at an angle to the natural slope, because this induces a differential charge of silt. Meanders can also be made to develop progressively upstream by injecting silt. Naturally-developed meanders follow definite laws as regards curvature, meander length, and meander breadth, whereas bends do not.

The model experiments carried out by T. M. Chacinski and J. R. D. Francis were done under quite unnatural conditions, which were imposed in vertical-sided flumes with unnatural width to depth ratios, and consequently bore no relationship to natural field conditions, as clearly explained by Gerard Matthes and as quoted by the author.

References

INGLIS, CLAUDE, The behaviour and control of rivers and canals, chap. 4, Meandering of rivers, Res. Pub. 13, Central Waterpower, Irrigation, and Navigation Res. Sta., Poona, 1942 (obtainable from Publications Branch, India House, Aldwych, London, W.C. 2, England).

INGLIS, CLAUDE, Meanders and their bearing on river training, Inst. Civ. Eng., Maritime and Waterways Paper 7, 1947.

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J. R. P. Francis and I referred to certain experiments made here concerning meandering channels which seem to prove beyond question that different kinds of helicoidal motion do occur in bends, and that these motions are greatly influenced by the nature of the motion existing at the entrance to each bend. It may perhaps be of interest to amplify our previous remarks by emphasizing that the helicoidal motions described are not restricted to the rather artificial deep and narrow channel shown in our previous communication, but definitely also have been measured in a channel whose ratio of width to depth is 20:1, and indeed we have observed them with a width to depth ratio of 80:1. Also they were measured in a channel with triangular section having deep water near the outer bank as in a river.

The helicoidal flows described are certainly small compared with the main discharge, but their observed action in sweeping bed-load particles transversely seems to suggest that they may well control at least some stages of the whole erosion phenomena.

Inglis mentions an experiment in which he observed meanders developing progressively upstream by injecting silt. This interesting evidence of an action proceeding upstream does not necessarily invalidate the present suggestion of helicoidal action passing downstream with the flow, and, while on the whole the field evidence remains inconclusive, there are certainly many well-described cases in which the secondary flows of the kinds measured here were observed in natural rivers.

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Inglis' communication on the meander problem is of great interest. With special reference to the experiment in which meanders were shown to develop upstream by injecting silt, it may be noted that the writer's theory seems to be well in agreement with this evidence, observing the fact that waves may travel upstream when the velocity is below the critical velocity.

The discussion by Chacinski and Francis is a little confusing. Whereas their first statement seemed to convey the meaning that helicoidal flow, caused by the entrance conditions, is the one controlling factor in meandering, the answer to Inglis' communication is rather cautious in this respect. In the writer's opinion it would appear sufficient to point out the ample evidence, put forward by G. H. Matthes and others, that helicoidal flow does not occur in some, if any, meandering rivers, at least not to any appreciable extent. Apparently, the tests carried out at the Imperial College, and previously referred to, have only a minor bearing on the pure meander problem under consideration.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

HOUK, IVAN E., Irrigation Engineering, Vol. 1, Agricultural and Hydrological Phases, John Wiley and Sons, 545 pp., 1951, $9.00.

This is the first of two volumes on irrigation engineering written by Ivan Houk. The second volume is to deal with planning and constructural aspects of irrigation engineering. In keeping with the high standards of all works by Houk, this book rates as a textbook of the hydrology of the West. As the author states, the book will serve very well both as a text for students of irrigation and as a reference for practicing engineers and hydrologists. There are 16 chapters each addressed to some phase of engineering hydrology, including climate, quantity and quality of water supplies, soils, soil moisture, and evaporation. The scope of the book adequately covers the broader phases of irrigation, agriculture, and hydrology, with greater emphasis on the latter.

Like most textbooks, this book reports on the state of the art as it exists in the established record. The job of the textbook writer is to digest and condense the literature for the student and the engineer, and thereby serve to reduce the lag between research and practice. There is inherent, of course, the possibility of giving undue prominence to an out-of-date source, but for the most part Houk has kept abreast of the latest developments.

It would be possible for the critical reviewer to discuss or quarrel with nearly every line or every item of a textbook. Few parts of hydrology are direct and simple. Every statement can be expanded into a paragraph, each paragraph into a page, and so on. For example, consider the statement on page 209 that "with stream-flow records of 150 years or more, flood magnitudes should be fairly well defined." What appears here to be a fairly straightforward summary of a statistical fact, actually becomes a lead to a vast literature on climatic sequences and the effects of man on stream regimen. The statisticians' line of decreasing error with length of record tends ultimately to exceed the limit of homogeneity of a stream-flow record. New variables are introduced of which a 150-year record is actually "a small sample." This does not in the least destroy the practical utility of a textbook, but tends to limit its usefulness as a source for research, and makes it important for the serious student to consult the well-selected bibliographies that follow each chapter.

There is so much that is well done that the writer hesitates to call attention to a few minor deficiencies. The method used in the western United States in stream-flow forecasting is now more general and flexible than the "percentage method" (as stated on pp. 232-233) as it was first presented by J. E. Church some years ago. The practice is to consider water equivalent of snow as one dependent variable among others in a multiple correlation. The percentage of normal is not essential in the method.

Although ground water continues about 25 pct of the American irrigation economy, substantially less than that percentage of the book is devoted to that subject. Similarly it is believed that the subject of reservoir sedimentation could have more space than 2 1/2 pages. Also missing is an adequate treatment of the growing irigation of crops in the otherwise humid East. There are large plantations such as that of the Seabrook Farms in New Jersey based on the use of water for irrigation during dry spells that occur nearly every summer in the East. As Thornthwaite showed some years ago, the evapotranspiration demands often exceed that supplied by rainfall in many places in the East, and irrigation water must be supplied if maximum crop production is to be maintained.

The reference that the heat-balance or the mass-transfer methods of determining evaporation noted on page 257 are impractical, seems to miss the point behind these methods. They were not proposed for measurement of evaporation from "existing weather records" but as a means for using existing geophysical knowledge and existing kinds of instruments for accurate measurement of evaporation where such measurements are needed either in research or in resource investigations.

The writer recommends the book without qualification to all who are interested in irrigation or in the hydrology in the West, although the price of $9.00 seems high for a book of this size.

W. B. LANGBEIN

Abstracts of the Pacific Southwest Regional Meeting, Stanford University, February 6-7, 1953

The following are abstracts of the papers presented at the meeting held by the Pacific Southwest Regional Board at Stanford University, February 6-7, 1953. These relate primarily to Meteorology and Hydrology, but some bear on other fields, notably Oceanography and Terrestrial Magnetism and Electricity.

Henry W. Anderson (California Forest and Range Experiment Station, Berkeley, Calif.) Detecting Hydrologic Effects of Changes in Watershed Condition--Double-mass plotting of hydrologic events against a meteorological control is one way of detecting the effects of changes in watershed condition. For example, this method of plotting showed what changes in sedimentation and peak inflow were associated with the occurrence of wildfires in the watershed above Gibraltar Reservoir. A meteorological control was calculated from the maximum daily precipitation of a storm and the precipitation during an antecedent period. Sedimentation of the reservoir and peak inflow were seen to have increased markedly following the wildfires of 1932 and 1933, then to have decreased as the watershed recovered from the fires. The effects of such changes in watershed condition must be taken into account in estimating long-term average sedimentation and flood frequency from our short-term records.

W. Douglas Baines (Division of Mechanical Engineering, University of British Columbia, Vancouver, B. C., Canada) A Long-Period Effect of Tides on Fraser River Stages--(Full paper with abstract published in this issue of the Transactions, pages 733-736.)

Peter Berger (Corps of Engineers, United States Army, San Francisco, Calif.) Estimation of Net Long-Wave Radiation from Snow--The role that long-wave radiation plays in snow melt is indicated. Data are presented on long-wave radiation measurements over the snow-pack which were made by means of Gier-Dunkle radiometers at Central Sierra Snow Laboratory, elevation about 7000 ft, during October and November, 1951. Result of these measurements indicate that net long-wave radiation from the snow surface averaged 0.10 langleys per minute at night and about 0.07 langleys per minute during the day for periods of clear weather. Analyses are given pertinent to the development of empirical methods for reconstituting the results of the actual measurements. One such method was found to apply within a standard error of estimate of 0.018 ly/min in computing single hourly values for nighttime conditions. This method takes into account the effects of snow surface temperature, temperature and humidity of the 50-ft layer of air just above the snow, and cloud height and cover. The method has not as yet been tested for other conditions of weather and environment.

William L. S. Bottorf (Corps of Engineers, United States Army, San Francisco, Calif.) An Empirical Method of Forecasting Critical Snow-Melt Inflow Rates to Pine Flat Reservoir--An empirical approach to forecasting high rates of stream flow resulting from springtime snow melt over the Kings River basin in California is presented. The situation which existed in 1952 at the partially completed Pine Flat Reservoir and which gave rise to the study is described. The forecasting method involves recessions from known flows, a temperature index of snow melt, and an index of areal snow cover based on accumulated snow-melt index values after a specified condition of snow depth at key stations. In addition, a seasonal parameter was used to reflect the progressive change in the temperature-melt relationship during the spring and, in conjunction with the accumulated temperature index, to provide for depletion and change in mean elevation of areal snow cover. With these variables, statistical analyses were made of historical data, and empirical equations were derived for estimating future rates of flow. The equation which was adopted was tested by application to the 1952 flood as well as to the earlier large snow-melt floods on which the derivation was based. The results insofar as project needs were concerned appeared fairly good. However, being based on mean statistical measures, the method was insensitive to such rapid changes in rate of flow as occurred in the 1938 flood.

C. L. Bretschneider (Dept. of Oceanography, Texas A. and M. College, College Station, Texas), David K. Todd (College of Engineering, University of California, Berkeley, Calif.), and H. L. Kimberley (Dept. of Aerology, U. S. Naval Postgraduate School, Monterey, Calif.) Comparison of Wave Forecasting Procedures--Three forecasters made wave forecasts for the same period and from the same set of weather maps. Comparisons of wave heights and periods were made among the different forecasters. It was found that the heights of one forecaster were higher than those of the other two forecasters more than 90 pct of the time, but no other obvious differences in forecasts were apparent. The standard deviations of differences in forecasts averaged 4.1 ft for heights and 4.3 sec for periods. These differences may be attributed to each forecaster's interpretation of the meteorological elements used in wave forecasting. From three different sets of weather maps for the same period one forecaster made separate forecasts. The standard deviations of differences in heights averaged 2.5 ft, and 3.8 sec for periods. These discrepancies were due to differences in map analysis and to the method of application of the wave forecasting theory. Weather maps of different time intervals also introduce discrepancies in wave forecasts even though the forecaster may be consistent in the interpretation of the meteorological elements.

Frederick A. Brooks and Herbert B. Schultz (Division of Agricultural Engineering, University of California, Davis, Calif.) Nocturnal Cooling of Foliage, Fruit, and Ground Interpreted by Measurements of Thermal Radiation Loss--The rate of nocturnal radiation loss (ranging from 15 to 30 Btu/hr ft^2 on clear nights) is now easily measured with the University of California (Gier-Dunkle) plate radiometer. Consequently the observed degrees of cooling below air temperature of exposed foliage, fruit, and ground surfaces are substantiated by known heat-transfer factors when the velocity of air flow through the tree depth of the orchard also is measured. For the very low velocities through the foliage the calculations showed temperature depressions ranging from one to seven degrees F as observed, depending of course on the extent of exposure to the cold sky. The convection-to-radiation transfer chart made up for spheres, cylinders, and plates is based on radiation loss from projected area because of the one-sided exposure to cold sky while the convection transfer is based on the whole surface. Using heated thermocouple anemometers to measure the very low velocities through the foliage, typical velocity ratios were found in the foliage versus over tree in the rather consistent density-current system observed at Riverside. A ratio of 3 to 1 is a fair average between over trees (at 26 ft) and in foliage (80 inches). Secondly, minimum orchard temperatures have been found to correlate well with observed net radiation and the previous day's maximum soil temperature at 4-inch depth. Curves have been drawn which can be used in predicting local minimum temperatures to about ± 1 1/4°F on calm nights under steady conditions. Naturally this method would not free the frost forecaster from considering the many other weather factors involved as described in F. D. Young's discussion [Mon. Wea. Rev., v. 58, p. 187, 1930].

Joseph I. Burns (Division of Water Resources, State of California, Sacramento, Calif.) Small-Scale Topographic Effects on Precipitation Distribution in San Dimas Experimental Forest--(Full paper with abstract published in this issue of the Transactions, pages 761-768.)

Edward M. Carlstead (Dept. of Aerology, U. S. Naval Postgraduate School, Monterey, Calif.) A Study of Constant Absolute Vorticity Trajectories on Isentropic Surfaces--It is demonstrated that the use of Constant Absolute Vorticity trajectories to forecast the wind is better applied to isentropic charts than to constant pressure charts. The vorticity equation for an isentropic surface is derived in a form similar to Rossby's but with fewer restrictive assumptions. A one-month series of isentropic and 500-mb concurrent charts chosen at random were analyzed. Using a simple table developed by Wobus, the future positions of particles were forecast on both sets of charts by CAV trajectories. These forecast winds were verified by actual data and the results are treated statistically showing forecasts made on isentropic charts to be significantly better than like forecasts made on concurrent 500-mb charts.

Ning Chien (College of Engineering, University of California, Berkeley, Calif.) Can the Rate of Wash Load Be Predicted from the Bed-Load Function?--(Full paper with abstract has been approved for publication in the Transactions and will appear under the joint authorship of H. A. Einstein and Ning Chien.)

Arnold Court (Dept. of Geography, University of California, Berkeley, Calif.) Rainfall Intensity--Rainfall amounts at any given place during a fixed period (month, season, year) have been found, in a study still in progress, to be directly proportional to the three-halves power of the duration (in hours or days) of the precipitation: $R = BD^{3/2}$. The coefficient, B, is a useful measure of precipitation intensity, varying from place to place, and throughout the year at any one place; it is termed the "imbrity" (from the Latin for "rain-shower"). Validity of the 3/2 power relationship is shown by plotting, for example, monthly rainfall amounts against the 3/2 power of the corresponding number of days of rain. Such diagrams of nearly 50 years of data, from each of a dozen places in all parts of the United States, appears fitted best by straight lines, with varying slopes, or imbrities. Scatter of points about these straight lines increases with distance from the origin, so that for any month the average of the individual imbrity values is adequate for computing the average imbrity.

Lloyd D. Doneen (Dept. of Irrigation, University of California, Davis, Calif.) The Quality of Water for Irrigation as Affected by Salinity--The paper is a partial report on the quality of irrigation water. It is principally concerned with the salts of irrigation water which form salines in the soil. As the slightly soluble salts of an irrigation water are precipitated, the method eliminates these salts in calculating the potential salinity which is listed as "effective salinity." New conversion factors have been listed for changing from milliequivalent to parts per million, or pounds of salt per acre foot for the soluble salts of effective salinity. A new standard based on the milliequivalent effective salinity has been suggested for the irrigation waters. This standard lists three salt concentrations (effective salinity) of the irrigation water, and three soil conditions that will affect salination of a soil, thus giving a total of nine classes. The application of these new standards is discussed in relation to salt accumulation in the soil under present-day irrigation practices.

Maurice A. Garbell (Garbell Research Foundation, San Francisco, Calif.) The Visual Range in Daylight, Darkness, and Twilight--During the twilight periods of dusk and dawn, the downward slant visual range of an airborne observer (for example, the pilot of an aircraft) may be severely decreased by the relatively great foreground brightness of the cloud or haze masses prevailing at the elevation of the aircraft while the Sun is still above the pilot's horizon, whereas the brightness and the brightness contrast of any visual target on the Earth's surface is relatively small since the Sun is below the ground-level horizon. A typical numerical example is shown in the following: If the slant visual range of an aircraft pilot circling an airport at 1000 ft is 3 1/2 miles in daylight, it will be reduced to 2 1/2 miles during the twilight period before it will increase to four miles in darkness. This entire transition, and possible critical decrease in the pilot's slant visual range, cannot be deduced from surface measurements alone since the horizontal visual range at the ground surface (WBAN "visibility") increases gradually from 3 1/2 miles in daylight to four miles in darkness without any comparable dip during the twilight period. In order to obtain numerical guidance, a generally applicable calculation method was developed.

G. J. Haltiner (Dept. of Aerology, U. S. Naval Postgraduate School, Monterey, Calif.) Dynamic Instability in Free-Surface Flows--Using the equations of motion and the boundary conditions, an integral condition is derived for dynamic instability of two-dimensional surface waves in an inviscid, non-divergent, barotropic fluid with an arbitrary velocity field. The condition involves the parameter's velocity field as well as gravity. The criterion is applied to several types of velocity profiles. In one case where $U''(z) < 0$ and $U'(h) = 0$ ($z = h$, being the surface), the waves with phase velocity less than the maximum current velocity are neutral, and unstable waves have a phase velocity greater than the maximum current velocity.

James A. Harder (College of Engineering, University of California, Berkeley, Calif.) Velocity Distribution and the Boundary Layer at Channel Bends--(Full paper with abstract has been approved for publication in the Transactions and will appear soon under the joint authorship of H. A. Einstein and James A. Harder.)

James A. Harder and Frederick L. Hotes (College of Engineering, University of California, Berkeley, Calif.) Model Studies of Sea-Water Intrusion--A three-dimensional sand model of a pressure aquifer with differential fluid densities has been used to study the movement of the sea-water wedge and its behavior under the action of barrier injection wells. An equation has been developed for the equilibrium state of the wedge and verified experimentally. It shows that the distance from the sea inland to the toe of the wedge is directly proportional to the aquifer transmissibility, the thickness of the aquifer, and the relative density of the salt and fresh water; while being inversely proportional to the rate of fresh water flow to the sea. Barrier injection wells will prevent sea-water intrusion by providing the required fresh-water outflow. However, any portion of the salt-water wedge inland from the line of influence of the injection wells will be cut off and will continue to flow inland at a faster rate. Furthermore, the injection rate must be sufficient to supply not only the requisite seaward flow but also to supply an additional quantity of fresh water equal to the existing overdraft. This latter quantity will usually be substantially greater than the former.

Carver E. Hildebrand (Corps of Engineers, United States Army, San Francisco, Calif.) A Unit Hydrograph Method of Hydrograph Synthesis for Snow-Covered Areas--The problem of applying unit-hydrograph principles to the relatively low rates of runoff from melting snow is considered, and a method is proposed whereby two unit hydrographs, one for surface flow and the other for groundwater, may be used to synthesize snow-melt hydrographs. From a single S-curve reflecting the gross runoff characteristics of the drainage basin, two unit hydrographs of different periods are derived. One fine-interval unit hydrograph reflects the early, rapidly changing, primarily surface-flow rates, while the other, coarse-interval unit hydrograph reflects the long, slowly changing, stream-recession, thus reducing the computations necessary in the application of the method. Interrelationships between S-curves and unit hydrographs of various periods are discussed in connection with the foregoing. A technique is given whereby the time base of the S-curve, and hence the unit hydrographs, may be varied to reflect variations in basin storage resulting from changes in snow cover and depth. Reconstitutions of two discharge hydrographs for the Central Sierra Snow Laboratory basin of four square miles (Soda Springs, Calif.) are presented, one resulting from a combination of rain and snow melt and the other from snow melt alone. The method also has been applied to the reconstitution of flood hydrographs for a number of other snow-covered drainage basins of the western United States up to 10,000 sq mi in area.

R. E. Holzer and G. F. Schilling (Institute of Geophysics, University of California, Los Angeles, Calif.) Atmospheric-Electric Measurements at High Elevations--Simultaneous measurements of the potential gradient and atmospheric conductivity were made at pairs of mountain stations in California at elevations from 550 to 3800 m MSL between February and September, 1952. Certain systematic trends in the data have been found at the higher elevations. The mean diurnal curves of computed air-earth current density approximate the ocean diurnal curves both in shape and relative amplitude. The diurnal potential-gradient curve at the highest elevation, 3800 m, is strikingly smooth and consistent from one day to the next. The evidence strongly indicates that at elevations of 3000 m and above the air-earth current density is largely determined by the potential difference between the Earth and the ionosphere rather than by the perturbations of the lower atmosphere. In the range of altitudes studied the mean conductivity on mountain tops is greater than the mean conductivity in the free atmosphere at the same level. This is apparently the result of a greater atmospheric ionization rate on mountain tops due to radioactivity of the Earth's crust. In spite of the difference in absolute magnitudes, the relative rate of increase of conductivity with altitude is nearly the same on mountain tops and in the free atmosphere. The diurnal oscillation of the conductivity decreases only slightly with the elevation of mountain stations suggesting that above 3000 m there is still a diurnal variation in the density of atmospheric nucleii, apparently confined to a relatively thin surface layer.

T. A. Jeeves, L. LeCam, J. Neyman, and E. L. Scott (Statistical Laboratory, University of California, Berkeley, Calif.) Further Contributions to the Evaluation of Cloud-Seeding Experiments--The validity of the evaluation of cloud-seeding operations, using the relation between the precipitation in the target area and in the comparison area established from past experience, depends on whether or not this relation is stable from one year to the next. The relation between the rainfall in the Carizzo Plain area and in the coastal area immediately to the west depends on the direction of the airflow prevailing during a storm: westerly air flow favors the coast, and southerly, the Carizzo Plain. The height of the 700-mb pressure level played a similar role. In the intervening months, efforts were made to determine whether or not this important phenomenon is an exception, characterizing the two particular areas mentioned or whether it is more or less a rule. Computations were performed for two more locations, the southern Sierra as target with nearby stations as the comparison area and the Santa Clara Valley (target) with the coastal strip to the southwest (comparison), and for several meteorological factors. In both cases it was found that the regression of the rainfall in the target on that in the comparison area depends on various factors of the weather. It follows that regression analysis can be used for the evaluation of cloud-seeding operations only in relation to particular types of storms that must be established in a preliminary analysis of past records.

Gerald J. Lieberman (Dept. of Statistics, Stanford University, Palo Alto, Calif.) An Evaluation of the 1951-1952 Cloud-Seeding Operation in Santa Clara County, California--A statistical study of the effect of cloud seeding in Santa Clara County during the year 1951-1952 was made. The study indicated that rainfall results obtained on the basis of available data could have been attributed to chance with a fairly large probability. If seeding had increased the rainfall in those storms which were seeded by as much as 30 pct, the test applied would have picked it up.

W. V. Louthern and W. S. Houston (Dept. of Aerology, U. S. Naval Postgraduate School, Monterey, Calif.) 500 Millibar Pressure of Diurnal Height Changes--Fourteen months of data from each of 72 United States and Canadian upper-air stations are processed in order to determine the monthly-mean 12-hour diurnal height change. This change is found to have a magnitude of as much as 90 ft for certain stations in Canada but is limited to the range of ±40 ft for continental United States stations. Statistical tests based on the Students-t distribution show that the 12-hr diurnal height changes, as computed for the average station considered, have a probability of 0.7 of being within plus or minus five feet of the true value, while the probability is 0.95 that the computed 12-hour diurnal height changes are within ±25 ft of the true value. A comparison between the 500-mb 12-hour diurnal height changes and the surface 12-hour diurnal pressure changes show a remarkable similarity in the seasonal variation of the two quantities.

M. Manohar (College of Engineering, University of California, Berkeley, Calif.) Part-Full Flow in Model Culvert Pipes--In this study, effects of part-full flow through a sharp-edged inlet and a rounded inlet fitted to a lucite pipe four inches in diameter and 35 ft long are analyzed experimentally and analytically. From about 400 test runs made on supercritical slopes with no tailwater pool at the outlet, it is found that the sharp-edged inlet acts as a circular weir for depths up to the top of the pipe and thereafter as an orifice with a coefficient of discharge of 0.624 until the pipe flows full. Flow through the rounded inlet is found to be similar to open-channel flow for heads up to the top of the pipe with critical depths occurring at the entrance. The types of flow that are noticed for higher heads preceding the full flow condition are termed slug and mixed flow phenomena. The lengths of slugs which move down-stream after their formation at the entrance are found to depend upon the total head at the entrance, and barrel friction loss within the slug section. In mixed flow phenomena it is found that the negative pressure inside the pipe near the entrance is equal to the total head at the entrance.

David H. Miller (Dept. of Geography, University of California, Berkeley, Calif.) Snow Cover And Snowmelt Runoff: The Need for Observation--Depletion of snow cover in several spring seasons in four drainage basins in the Rockies and Sierra displays a relation to ablation of snowpack mass that is fairly consistent from year to year and basin to basin. Variations are ascribed to homogeneity of terrain (allowing more melt before reduction of cover) or to depth of initial snowpack. An acceleration in yield often appears at about 60 pct of initial cover. Basins or years with shallow snow may experience considerable depletion of cover per unit of early runoff, only 60 pct remaining when half the season's runoff has passed. Wetter areas or seasons, or basins with more homogeneous terrain, experience the midpoint of runoff at higher values of snow cover. Peak flows are possible at more than 90 pct cover if antecedent weather and upper-air patterns are favorable. Plotting snow cover against volume of subsequent runoff shows that curves for different basins and different years converge at a date when about five inches runoff and 30 pct cover still remain on the basin. A program of snow-cover observations is suggested to serve operational purposes and to aid research on moisture and thermal factors. Such a program also would be a step toward a complete hydroclimatic picture of a drainage area for use in future hydrologic investigations.

Joseph W. Mixsell (Corps of Engineers, United States Army, San Francisco, Calif.) Influence of Terrain Characteristic on Snowpack Water Equivalent--A summary is presented of several exploratory studies conducted to evaluate the influence of elevation, slope, aspect, curvature, exposure, and vegetation on the distribution of snowpack water equivalent in two mountain watersheds. One of these, the Upper Columbia Snow Laboratory, (20.7 sq mi) is in the Rocky Mountains just west of the Continental Divide at Summit, Montana. The other, the Central Sierra Snow Laboratory (3.96 sq mi), is just west of the divide of the Sierra Nevada near Soda Springs, California. Snowpack water equivalent seems generally greater at locations of either higher elevation, flatter slope, northerly aspect, concave curvature, or restricted exposure. The relationship of aspect, vertical curvature, slope, and elevation to water equivalent is shown by coaxial nomograph for the Sierra data for June, 1950. No definite evaluation of the effect of vegetation could be made. The effects of weather on the distribution of water equivalent could not be taken into account because of insufficient data.

J. F. O'Connor (Dept. of Aerology, U. S. Naval Postgraduate School, Monterey, Calif.) Upper Atmosphere Pressure Changes--The principal mechanisms of upper pressure changes are suggested as being the propagation of high winds into areas of weaker pressure gradients. Where the weaker pressure fields are cyclonically curved, pressure falls occur to the left of the propagating speed maxima. Where the weaker gradients are anticyclonically curved, pressure rises occur principally to the right of the propagating high winds. Thus upper isallohyptic areas depend on the existence of speed maxima along the jet stream. The falling heights in cyclonic areas downstream from speed maxima are the result of horizontal transversal divergence produced by super-gradient winds overcompensating longitudinal convergence. Rising heights occur in regions of strong cyclonic gradient in conjunction with speed minima which produce overcompensating transversal convergence because of the subgradient wind speeds. Rising heights in anticyclonic gradients caused by approaching high speed winds are the result of horizontal convergence which tends to be a maximum at the inflection point between the ridge and its adjacent downstream trough. The falling heights are associated with lowering of the tropopause, stratospheric warming, and tropospheric cooling, suggesting a level of maximum divergence on about 300 mb with sinking above, and ascent below, this level. Conversely rising heights aloft are associated with the opposite effects relative to this level. Thus the 300-mb surface should be the most efficacious level for forecasting upper isallohyptic effects. Since the curvature in anticyclonic motion is critical at certain wind speeds, or with certain gradients of contours, sharply curved anti-cyclonic ridges are unstable either when excessively fast air speeds are observed approaching such ridges or when the gradient in the ridge is excessive. Such ridges collapse rapidly, causing large height rises downstream and large height falls in the ridge area. This is analagous to a peaked ocean wave breaking toward the beach downstream.

R. R. Putz (Institute of Engineering Research, University of California, Berkeley, Calif.) The Analysis of Ocean Waves as Random Processes--The theory of random processes may be advantageously applied to the study of empirical records of waves in the ocean provided suitable probabilistic models can be found. The two complementary aspects of such models, namely, the statistical distribution of ordinates and the spectral distribution of energy, are discussed. The fundamental features of the special type of process known as gaussian are presented, together with experimental evidence accumulated thus far. The implications of this model are developed, certain of these being found to explain previously reported results. It is suggested that a program of rapid analyses, either mechanical, graphical, or numerical, of wave records may be capable of providing a few parameters characterizing each wave record more or less closely depending upon the degree to which spectra fall into common classes.

Robert J. Renard (Dept. of Aerology, U. S. Naval Postgraduate School, Monterey, Calif.), Lawrence A. Hughes, and Betty Jordan (University of Chicago, Chicago, Illinois) A Nomogram for Computing Gradient Winds with Special Reference to a Test of its Use at 300 Millibars--A nomogram is offered which basically solves for the gradient wind, while indirectly taking trajectory radius into account. The nomogram employs radius of curvature of streamlines (contours), geostrophic wind speed, latitude at the point of computation, and speed of the pressure system in terms of trough and ridge speed. Limitations and facility of its use with varying speeds of pressure systems and radii of curvature up to 80° latitude are outlined. A radius of curvature overlay employing one set of curved lines, multilabeled for use at latitudes 30-60°, accompanies the nomogram. Results obtained from a statistical check, comparing computed with observed winds $>$ 25 knots for a 13-day period at 300 mb in November, 1951, over the United States and the British Isles, (sample = 468 winds), are outlined below. (The contour analysis used to compute the winds is accomplished, essentially, without the aid of wind data). (1) In both the cyclonic and anticyclonic cases per cent deviations of the computed geostrophic (V_{ge}), and gradient speeds (V_{gr}) from the observed speeds (V_o) are initially tabulated and compared (a) with cyclonically curved contours (the comparison shows V_{gr} is the best approximation to V_o, especially for $V_o > 50$ knots; a curve of per cent deviations of V_{gr} from V_o is quite symmetrical with a mode at about zero per cent); (b) with anticyclonically curved contours (the comparison shows V_{ge} is the best approximation to V_o; a curve of per cent deviations of V_{ge} from V_o, range 25-50 knots, shows accuracy similar to (1a) while with $V_o > 50$ knots similar accuracy is achieved by increasing V_{ge} 20 pct); (2) with contours having radii of curvature $>$ of 80° latitude (the curve of per cent deviations of V_{ge} from V_o shows accuracy similar to (1a) above). There is the suggestion that winds with anticyclonically curved contours are non-gradient in character, since half of the cases in this category exhibit radii of curvature of contours smaller than the minimum radii possible with balanced gradient flow.

E. R. Rowe (Division of Highways, State of California, San Francisco, Calif.) Analysis of Hourly Precipitation Records for Use in Highway Drainage Design, Part 2, Variation of Intensity Frequency in the Coastal Belt near San Francisco Bay--In order to determine the local variation of P_{60} and the ratio of P_{60}/10-yr storm, an individual analysis was made of 33 precipitation records in the coastal belt near San Francisco Bay. Plotting frequencies to be used on special Arithmetical Probability Charts were computed in the form of tables of $F(x_m)$ versus m for various values of n. P_{60} isopleths and the ratio of P_{60}/10-yr storm were determined by plotting the graphical solution of the above charts on topographic maps and correlating with other precipitation.

R. R. Rowe (Division of Highways, State of California, Sacramento, Calif.) Analysis of Hourly Precipitation Records for Use in Highway Drainage Design, Part 1, Computation of Mean Intensity Frequency for Climatic Regions of California--The California Division of Highways uses a nomograph, known as Culvert Chart A, to compute a design discharge from topographic factors and a precipitation factor called P_{60}, which is defined as the mean precipitation for a duration of 60 minutes likely to be equalled or exceeded once in 100 years. Hourly records for about ten years at 336 stations in California were analyzed by probability charts, combining ten to 20 records for each of 30 climatic regions into one long-period pseudo-record, obtaining a mean value of P_{60} for the region.

Verne H. Scott (Dept. of Irrigation, University of California, Davis, Calif.) Soil Temperature and Infiltration Studies on Burned and Unburned Upland Soils--Many factors contribute to the maximum and duration of soil temperatures reached during burning. Two of the most important are the brush type and whether it is standing or knocked down. The maximum soil temperature recorded at a 1/8 to 1/4 inch depth at one site of standing chamise brush was 266°C whereas in the same brush type knocked down a maximum of over 400°C was recorded. The maximums and duration of temperature reached under field conditions of control burns are within the range which may be expected to produce changes in soil structure that could in turn influence the infiltration rate.

Single-ring infiltrometers were found to be satisfactory for measuring relative infiltration rates of these burned and unburned upland soils. Six areas representing five soil types were tested. In every case the infiltration rates of the burned soils measured at the end of the first 15-minute and one-hour periods after water was added to the infiltrometer were higher than those of the unburned. In all the cases for these periods of time the maximum difference in rates was 18.73 and 4.07 inches per hour and the minimum difference 0.49 and 0.31 inches per hour.

Parker D. Trask (Institute of Engineering Research, University of California, Berkeley, Calif.) The Alluvial Flood (Huayco) Problem of the Peruvian Andes--The Cordillera Blanca area of the Peruvian Andes from time to time suffers severe floods, known locally as huaycos, caused by bursting glacial lakes or sudden rainstorms. In their initial phases they are similar to other floods but in their final stages the water contains so much soil and rock that a giant mudflow is formed. At the end of the flood this mass of alluvial material clogs the valleys to a considerable height. In a recent flood the fill was 140 ft in one place, and a boulder 15 ft in diameter plugged the entrance of a road tunnel 80 ft above the stream bed. In the mountains the alluvial material contains a large proportion of rock debris but on the lowlands at the foot of the mountains it may consist mostly of mud and silt. The manner in which the valleys are clogged with debris is suggestive of the way in which gullies in arid parts of the United States have been filled with sediment.

William G. Van Dorn (Scripps Institution of Oceanography, University of California, La Jolla, Calif.) Wind Stress over Water--The wind-induced slope of the surface of an 800-ft model-yacht pond has been measured to a relative accuracy of 5×10^{-7}. This slope, which is proportional to the sum of the surface and bottom stresses, is shown to be the result of two effects: first, a tangential friction drag, which is invariably present and proportional to the square of the windspeed; and second, a form drag, which occurs only after the wind has increased above a certain critical value. The second effect is related to surface waves. Application of a detergent to the water eliminates both waves and form drag. The surface current was proportional to the wind speed and independent of waves. The slope increased with heavy rain, and a theoretical model is proposed which adequately predicts the observed increase. The present study was modeled closely after Keulegan's experiments in a 60-ft laboratory channel. The results of the two studies agree quantitatively.

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NOTES AND PERSONALIA

NOTES

Corrigendum--In the issue of October, 1952, in the paper by Chia-Shun Yih entitled Free Convection Due to a Line Source of Heat, on page 671, in the computation following Eq. (27), the correct relations are

$$\text{If } 3\sigma A = 2B, \text{ then } \sigma = 5/9 \text{ and } K = 8A^2B^2/3$$

$$\text{If } 3\sigma A = 4B, \text{ then } \sigma = 2 \text{ and } K = 4A^2B^2$$

The subsequent results must be duly modified. Also, Eq. (17) should be corrected by substituting h for θ. These corrections were sent to the author by Edgar Bendor of the Imperial College of Science, London, England.

Scientific Translations Center established at the Library of Congress--The National Science Foundation has established a Scientific Translations Center at the Library of Congress in cooperation with the Atomic Energy Commission. The translations will be collected from many sources. The Center will provide photo-duplicating service. Inquiries should be sent to Scientific Translations Center, Science Division, Library of Congress, Washington 25, D. C.

Establishment of Scientific Register--The National Science Foundation, charged by law with the maintenance of an inventory of scientific manpower, is in the process of establishing this Register, utilizing material available from previous endeavors. Geophysicists will be covered by cooperative effort of the American Geophysical Union with the American Geological Institute. Members should be on the lookout for their questionaires which should go forward in the late autumn or early winter.

Research and fellowship programs of the Shell Oil Co.--The Shell Oil Co. is continuing and increasing its research grants and fellowship awards during the school year 1953-54. It is increasing the number of grants from 12 to 14, with a total of $70,000. The fellowships have been increased from 45 to 48 in number, with a total award of $107,500. The institutions receiving grants are California Institute of Technology, Carnegie Institute of Technology, University of Chicago, Harvard University, Massachusetts Institute of Technology, Princeton University, University of Rochester, Stanford University, and Yale University. The fellowship program is administered directly by the Shell Fellowship Committee, Shell Oil Co., 50 West 50th St., New York 20, N. Y.

Fellowship program of the Humble Oil and Refining Co.--The Humble Oil and Refining Co. has provided 20 fellowships in various fields of science involving a total of $40,800 for the School year 1953-54. Grants for these fellowships have been made to Rice Institute, University of Texas, Texas A. and M. College, University of Oklahoma, Louisiana State University, Georgia Institute of Technology, University of California at Los Angeles, Alabama Polytechnic Institute, and Massachusetts Institute of Technology. The funds are administered by these institutions. The program has now extended over several years.

Conference on Resources for the Future--The Mid-Century Conference on Resources for the Future will be held in Washington, D. C., December 2 to 4, 1953 to bring together interests representing private business, labor, agriculture, education, and conservation, as well as local, state, federal, and international governmental agencies. Interested persons should get into touch with Resources for the Future, 1025 Connecticut Ave., N. W., Washington, D. C.

High-altitude research observatory in Alaska--A new high-altitude research observatory, chiefly for studying cosmic radiation, biology, and meteorology, has been established on the top of Mt. Wrangell, a 14,000-ft extinct volcano in Alaska, by Serge A. Korff of New York University and Terris Moore, President of the University of Alaska. It will serve as an inter-university research center. The materials for the huts and the equipment and supplies were dropped by air. It is believed that the only previous ascent to the top of this mountain was made in 1908.

High-altitude studies at the North Geomagnetic Pole--The Bureau of Aeronautics, the Office of Naval Research, and the Atomic Energy Commission joined their efforts during the summer months on Project Mushrat, a study of cosmic radiation and related phenomena by balloon and rockets at elevations well above 100,000 ft. In 1952, a similar expedition carried their studies to a peak altitude of 295,000 ft.

Work of the Western Speleological Institute--The Institute has completed its first year of active operation, which included a three-month California-Nevada speleological survey, the Bower Cave underwater explorations, reconnaissance of the Grand Canyon, and archaeological excavations of Crypt Cave in the field, and research into Karst and cave evolution, formation of shields in caves, and the hindcasting of climatic fluctuations from rock temperature distributions. A 200-page report has been issued. The President of this Institute is O. H. Truman, and Arthur Lange is a member of the staff. The address is Carson City, Nevada.

First Annual Conference on Earth Science Education--A conference, sponsored by the Departments of Geology and Geography of Bowling Green State University, Bowling Green, Ohio, will be held November 7, 1953 on the Campus of the University. This will be primarily for the benefit of public school science teachers. Interested persons should write to John R. Coash, Department of Geology, Bowling Green State University, Bowling Green, Ohio.

Index map of aerial photography--The U. S. Geological Survey has published a new index map showing the status of aerial photography in the United States. Interested persons should write to the Map Information Office, U. S. Geological Survey, Washington 25, D. C.

PERSONALIA

Konrad Buettner has accepted the appointment of Acting Associate Professor of Meteorology at the University of Washington.

Albert J. Z. Caan of Socony-Vacuum Oil Co. in New York, is now on a six-month assignment to the Exploration Department of the Deutsche Vacuum Oel A. G. in Celle, Germany.

Frank W. Edwards, who has been Director of Civil Engineering at Illinois Institute of Technology, has taken charge of the new Chicago office of the Stanley Engineering Co. of Muscatine, Iowa.

H. Garland Hershey of the Iowa Geological Survey has been elected President of the Iowa Academy of Science.

Walter L. Huber, Consulting Engineer of San Francisco, has been appointed a member of the Advisory Board of National Parks, Historic Sites, Buildings, and Monuments of the National Park Service.

Robert M. Hutchinson has recently taken his doctorate from the University of Texas and has accepted an assistant professorship at Kansas State College.

George C. Kennedy, formerly of the Department of Geology at Harvard University, has taken up duties as Professor of Geochemistry at the Institute of Geophysics of the University of California at Los Angeles.

Harry A. Marmer, Assistant Chief, Division of Tides and Currents, U. S. Coast and Geodetic Survey, retired August 31, 1953, after serving since 1907 with the Survey.

Brian H. Mason, until recently Associate Professor of Mineralogy at the University of Indiana, has taken up duties as Curator of Physical Geology and Mineralogy at the American Museum of Natural History.

Frank Neumann, Chief of the Seismology Branch, Division of Geophysics, U. S. Coast and Geodetic Survey, August 31, 1953, retired after serving with the Survey since 1911. He has accepted a position as Professor of Seismology at the University of Washington in Seattle.

H. Kirk Stephenson, formerly of the Los Alamos Scientific Laboratory, has taken up duties with the National Science Foundation as Program Director for the Earth sciences.

Jerome van de Erve, Eastern Area Hydrologic Engineer, U. S. Weather Bureau, since February 5, 1950, has transferred from Washington, D. C., to Sacramento, California, as Western Area Hydrologic Engineer. He will replace Vernon W. Rupp, who has resigned from government service to enter private business.

Gordon R. Williams of Knappen-Tippetts-Abbett-McCarthy, consulting engineers, has taken up duties as Associate Professor of Hydraulic Engineering at Massachusetts Institute of Technology.

He will continue in a consulting capacity with his former connection on projects on which he has been working.

Robert Walter Gay, Hydraulic Engineer for the Bureau of Reclamation at Boise, Idaho, died May 8, 1953 at the age of 72. He was born at Higganum, Conn., and took his baccalaureate degree from New York University in 1902. He taught at Lehigh University from 1903 to 1905, then at the University of Colorado from 1906 to 1909. From 1910 to 1918, he was Professor of Civil Engineering at Mississippi State College, then going into the service of the Memphis Morgan Engineering Co. From 1927 to 1936, he was in the service of the Corps of Engineers, following which he transferred to the Tennessee Valley Authority. In 1946 he transferred to the Bureau of Reclamation where he directed hydrologic studies in Region 1, retiring in 1950, but remaining as a Consultant of the Bureau. He had been a member of AGU since 1942.

Joseph S. Hollister, Consulting Geologist, died May 8, 1953 at the age of 49. He was born in Sacramento, Calif., and took his baccalaureate degree from Yale University, subsequently securing his doctorate at the University of Göttingen. His early work was devoted to problems of the structural history of California. He subsequently engaged in structural and paleogeographic studies of the Philippines and southern Chile. He had been a member of AGU since 1945.

Arne Arthur Jakkula, Executive Director of the Texas A. and M. Research Foundation, died May 30, 1953 at the age of 49. He was born at Hancock, Michigan, obtained his baccalaureate degree in 1926 and his master's degree in 1927, both from the University of Minnesota. In 1933, he took his doctorate from the University of Michigan and he was awarded a professional degree in civil engineering by the University of Minnesota in 1937. He devoted first ten years of his career to teaching of civil engineering at the University of Michigan. In 1937, he went to Texas A. and M. College as Professor of Structural Engineering, where he continued his work until his death. He had been a member of AGU since 1950.

William Meiron Jones, Director of the Geophysical Observatory of the Department of Scientific and Industrial Research, Wellington, New Zealand, died March 15, 1953 at the age of 60. He was born at Papakura, Auckland, New Zealand, and took his master's degree at the University of New Zealand in mathematics in 1914 and a degree in physics at Oxford University in 1924. Upon his return to New Zealand, he was engaged in geological and geophysical surveys for the New Zealand Government, and the seismological work of the Dominion Observatory, and became director of the Geophysical Observatory in 1948. He had been a member of AGU since 1949.

John C. Kennedy, engineer in the Ohio River Division Laboratories of the Corps of Engineers in Cincinnati, died February 14, 1953 at the age of 50. He was born at Felicity, Ohio, attended Miami University at Oxford, Ohio, 1921-23, and obtained his baccalaureate degree from Ohio State University in 1933, subsequently taking graduate work at Ohio State and the University of Cincinnati. After his early work in Ohio, he was assigned by the Corps of Engineers to sedimentation studies at the Iowa Institute of Hydraulic Research in the late 1930's. He subsequently worked with the Ohio River Division of the Corps of Engineers, working on various projects and at the Mariemont Testing Laboratory. He was stricken in November, 1951. He had been a member of AGU since 1939.

Kaarel Kirde, formerly Professor of Physics at Tartu University (Dorpat), Estonia, died while Acting Professor of Physics at St. Olaf College, Northfield, Minnesota, May 25, 1953. He had been active on the Commission of Snow and Ice of the International Accociation of Hydrology.

Armin Otto Leuschner, Professor Emeritus of Astronomy of the University of California, died April 22, 1953, at the age of 85. He was one of the original members of the Union. He was born in Detroit, Michigan. He took his baccalaureate degree from the University of Michigan in 1888, did graduate work at the University of California, and received his doctorate from the University of Berlin. He subsequently received a number of honorary doctorates. He entered his professional work as an instructor in Mathematics at the University of California, which he served throughout his career until his retirement in 1938, at the same time serving for various periods on such special boards as the California Council of Defense and the California Earthquake Commission, and on various international bodies. He received numerous honors, both domestic and foreign for his outstanding contributions to astronomy and geodesy.

Guenter Loeser, scientist of the Air Force Cambridge Research Center, was killed in a helicopter accident in Nebraska on July 30, 1953. He was born in Dillingen in the Saar in 1914, and attended the Universities of Heidelburg, Hamburg, and Frankfort am Main, taking his doctorate in 1936. From 1936 to 1945, he was Director of the ballistic weather service and the laboratory for aerological instruments on the ordnance proving ground of the Krupp Company. From 1948 to 1951, he was the Chief Editor of Die Umschau. He came to the United States in 1951, and became a member of AGU in 1952.

Eric Rexford Miller, retired meteorologist, died April 8, 1952, at La Jolla, California, at the age of 73. He was born at Mt. Pleasant, Michigan, studied at the University of Arizona from 1896 to 1899, taking his degree some years later. He took his master's degree from the University of Wisconsin in 1921. He entered the service of the U. S. Weather Bureau in 1901, continuing in various capacities at Galveston, Tampa, New York, Washington, and Mt. Weather. In 1908, he took up duties as local forecaster at Madison, Wisconsin, where he served until his retirement. At Madison, he took up duties as lecturer in Meteorology and Climatology. His scientific investigations involved many aspects of meteorology and terrestrial magnetism. He had been a member of AGU since 1934.

Dagoberto Sardina, of the Argentinian Water and Power Board and the co-founder of snow surveying in the Argentine Andes, was killed by avalanche in a refuge hut while conducting snow research August 21, 1953, near the close of the southern winter.

James Bernard Ward, Engineering Geologist with Knappen-Tippetts-Abbett-McCarthy, Consulting Engineers, died July 9, 1952 while in Haiti, at the age of 38. He was born in North Carolina, and took his baccalaureate degree from the University of North Carolina in 1933. He devoted the first ten years of his professional career as a foundation geologist with the Tennessee Valley Authority, subsequently undertaking similar duties with the Corps of Engineers. Since 1947, he had undertaken engineering geological work with Knappen-Tippetts-Abbett-McCarthy in various parts of the world. He had been a member of AGU since 1950.

Frederick Eugene Wright, Petrologist of the Carnegie Institution of Washington, retired, died at his summer home in the Thousand Islands on August 25, 1953, at the age of 75. He was born in Marquette, Michigan. He took his doctorate from the University of Heidelberg in 1900, and received an honorary doctorate from the University of Michigan in 1940. He began his professional career as an Instructor at Michigan State College, soon entering upon duties with the Michigan State Geologist, assuming duties as State Geologist in 1904-1905. In 1906, he entered the service of the U. S. Geological Survey, which continued until 1917. He began work with the Carnegie Institution of Washington in 1906, also, as a research physicist and petrologist. This continued until his retirement in 1944, but he continued as a physicist on war work until 1946. He served as Vice President of the National Academy of Sciences from 1927-1931, subsequently serving for many years as Home Secretary. He had been a member of AGU since 1924.

SPECIAL ANNOUNCEMENTS

Meeting in Boston, December 28-30, 1953--The Thirty-First Regional Meeting of the American Geophysical Union will be held at the Somerset Hotel in Boston, December 30, 1953, in conjunction with the annual meeting of the American Association for the Advancement of Science. A one-day meeting is being arranged by a committee under the chairmanship of Helmut E. Landsberg. In addition, AGU is cosponsoring the Symposium on The Physics of the Upper Atmosphere being arranged by Section B (Physics) of the AAAS on December 28, The Symposium on Water for Industry being arranged by Section E (Geology) of the AAAS on December 29, and a general AAAS Symposium on The Sea Frontier also on December 29. For information regarding the program of AGU on the 30th, get into touch with Dr. Landsberg, 1053 Concord Ave., Belmont 78, Mass. With regard to the symposia, write to Raymond A Taylor, American Association for the Advancement of Science, 1515 Massachusetts Ave., N. W., Washington 5, D. C. The AGU committee for the meeting includes Elbert L. Eaton, Wallace E. Howell, Patrick M. Hurley, H. B. Kinnison, Daniel Linehan, J. Robert Moore, and James A. Peoples, Jr.

Pacific Southwest Regional Meeting, University of Southern California, January 29-30, 1954--The Thirty-Second Regional Meeting will be held at the University of Southern California at Los Angeles, January 29-30, 1954. Plans for this meeting are developing. Interested pershons should get into touch with Chairman Martin R. Huberty (Professor of Irrigation, University of California, Los Angeles, California) or Secretary R. Corday Counts, Jr. (Supervising District Forecaster, U. S. Weather Bureau, San Bruno, California) of the Pacific Southwest Regional Committee, or with members of the Committee on Local Arrangements (Stanley S. Butler or John Mann, University of Southern California).

Thirty-Fifth Annual Meeting, Washington, D. C., May 3-5, 1954--The Thirty-Fifth Annual Meeting will be held in Washington, D. C., May 3-5, 1954 (Monday to Wednesday), in accordance with the SPECIAL ANNOUNCEMENTS in the June issue [p. 510] and the August issue [p. 669]. Plans, in their preliminary stages are progressing well, with all Sections and the Union arranging for sessions. Place this meeting on your calendar, and make plans to come.

This announcement serves also as an invitation for members and others to send word of plans for papers to be presented. Titles of papers with three copies of the abstract should be sent as soon as possible, and not later than March 10, 1954, with advice concerning the time required (most papers are allowed from ten to 20 minutes) and the projection equipment needed. Send this word to the office of AGU at 1530 P Street, N. W., Washington 5, D. C., or to the Secretary of the appropriate Section, as follows:

Geodesy	Frank L. Culley	U. S. Coast and Geodetic Survey Washington 25, D. C.
Seismology	James A. Peoples, Jr.	39 Edgewater Drive Waltham 54, Mass.
Meteorology	Woodrow C. Jacobs	4302 Kentbury Drive Bethesda 14, Md.
Terrestrial Magnetism and Electricity	Leroy R. Alldredge	3133 Jennings Road Kensington, Md.
Oceanography	Donald W. Pritchard	Chesapeake Bay Institute RFD 2, Box 426a Annapolis, Md.
Volcanology	Felix Chayes	Geophysical Laboratory 2801 Upton Street, N. W. Washington 8, D. C.
Hydrology	Harry F. Blaney or Ralph N. Wilson (Program Chairman)	1509 P. O. and Court House Bldg. U. S. Dept. of Agriculture Los Angeles, Calif. 3322 Stanford Drive University Hill Hyattsville, Md.
Tectonophysics	James T. Wilson	Department of Geology University of Michigan Ann Arbor, Michigan

As the Section Secretaries reserve the right to close filled programs in advance of the date indicated, it is desirable that word concerning papers be sent in early.

It is the plan to publish abstracts in the program. Remember that an abstract is an opportunity to bring the important results of your work to all who see the program. It must be concise but comprehensive, and not exceed 200 words. Longer abstracts will be reduced to 200 words or omitted at the editor's discretion.

The Chairman of the Committee on Meetings (John N. Adkins, 5508 Cornish Rd., Bethesda 14, Md.) and Vice President Maurice Ewing (Lamont Geological Laboratory, Columbia University, Palisades, New York) who is arranging the Union sessions invite suggestions and comments that will be helpful in planning this meeting. Especially invited are comments relating to papers and symposia bearing on more than one Section.

Make hotel or room reservations directly with the hotel of your choice at an early date. Failing on the first attempt, bear in mind that advance bookings not taken up are cancelled two weeks in advance, so a follow-up request in mid-April may bring desired response. We are making block booking at two or three hotels again, an announcement concerning which will appear in the Special Announcements of the December, 1953, issue of the *Transactions*.

John N. Adkins, Chairman
Committee on Meetings

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THE ELECTRICAL CONDUCTIVITY OF THE ATMOSPHERE OVER THE PACIFIC OCEAN

Samuel C. Coroniti and Eldon Heaton

Abstract--The electrical conductivity of the atmosphere was measured over the Pacific Ocean. The measurements were made at altitudes of 3.8, 5.2, and 6.4 km and between geomagnetic latitudes of 22° and 45° N. The value of q computed from the measured conductivity values agrees very well with those derived from cosmic-ray data.

Introduction--*Carnegie* cruise data revealed that the negative electrical conductivity of free air over the ocean at sea level did not vary perceptibly with geomagnetic latitude [GISH and Others, 1945; FLEMING, 1949]. The object of this investigation was to study the behavior of the electrical conductivity of the free atmosphere at specified altitudes over the Pacific Ocean, namely, at 3.8, 5.2, and 6.4 km.

At these altitudes the concentration of nuclei is negligible; consequently, the negative conductivity, λ_-, can be expressed by the equation

$$\lambda_- = (q/\alpha)^{1/2}\ ek \times 300 \text{ statmho/cm} \quad \ldots\ldots\ldots\ldots (1)$$

where

q = rate of production of ion pairs/sec cm^3
α = recombination coefficient, having a numerical value of 1.6×10^{-6} at standard temperature and pressure
e = charge per ion, 4.77×10^{-10} statcoulomb, and
k = mobility of the small negative ions; its numerical value is approximately equal to 1.3 cm^2/volt sec at standard temperature and pressure

Since α, e, and k can be considered approximately constant at constant altitude, $\lambda \propto \sqrt{q}$, approximately.

Experimental procedure--A B-29 aircraft was equipped with a Gerdien-type aspirator which was mounted in the nose section. An account of the apparatus has been published elsewhere [CALLAHAN and Others, 1951]. Suffice it to say that the parameter λ was measured directly, and the temperature and pressure were observed values obtained from the regular aircraft instruments.

Four flights were made during January and February, 1952, three of them successful. The first one was from Travis Air Force Base, California, to Hickam Air Force Base, Honolulu, T. H., at an altitude of 12,500 ft (3.8 km). The return flight was at 17,000 ft (5.2 km). The third flight was from Travis to Hickam at 21,000 ft (6.4 km).

During these flights the electrical conductivity was recorded continuously on an 11-inch Brown electronic strip recorder, having a chart speed of one inch per minute (25.4 mm/min). The weather was monitored visually and pertinent comments about it were entered on the conductivity chart. The values of temperature, pressure, and position were taken from the navigator's log.

Discussion of results--Only fair-weather conductivity values were used, any which were associated with turbulence, fog, or clouds being discarded. The data were taken from the charts at each integral degree of latitude. Each value of conductivity is the average over a ±20-minute spread at each degree. The results of these flights are shown in Figure 1. The ordinate is expressed in conductivity in units of 10^{-4} statmho/cm, and the abscissa in degrees of geographic latitude.

Examination of these graphs shows that, generally, the conductivity increases with increasing latitude. This effect is not pronounced at 3.8 km. The weather during most of this flight was hazy

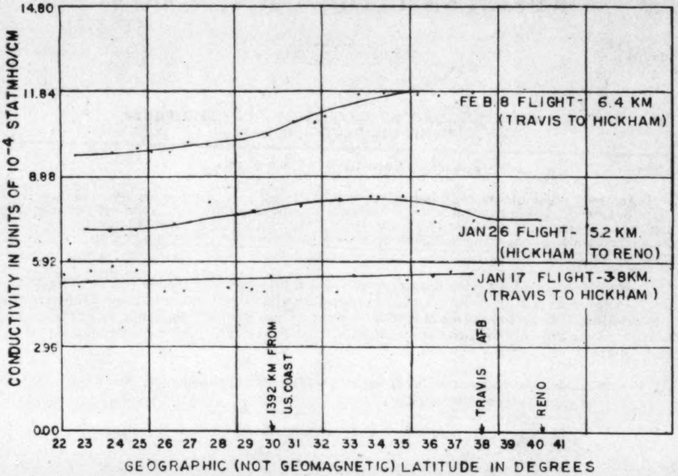

Fig. 1--Relationship of conductivity to geographic latitude

and turbulent; hence, it was difficult to use only fair-weather data. The scattering of the points about the straight line is evidence of the presence of nuclei. However, at 6.4 km a considerable decrease in conductivity was noted for latitude values greater than 35° N. This decrease is attributed to the presence of nuclei which were transported to this altitude from the ground. During this interval, large and rapid fluctuations of conductivity values were recorded. This fact is an indication of the presence of nuclei.

Comparing the contours of the curves shown in Figure 1 with the cosmic-ray latitude curves published by BOWEN, MILLIKAN, and NEHER [1938] and by MONTGOMERY [1949], one would deduce that the principal source of ionization at these altitudes is cosmic-ray energy. To establish this correlation, the rate of ion production, q, was computed by using the measured value of conductivity, λ_-, at the three altitudes and at the two fixed geomagnetic latitudes, 22° and 45° N. The corresponding locations are Hickam AFB, Honolulu, T. H., and Travis AFB, California. The equation used in the computation is

$$\lambda_- = 300 \text{ ek} \left[(q/\alpha)_{T=273}\right]^{1/2} \left[P_0/P\right]^{1/2} \left[T/T_0\right]^{9/4} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where P_0 is 760 mm Hg, T_0 is 273° K, and $(q/\alpha)_{T=273}$ is value of q/α at temperature T_0 and pressure P_0, and P and T are pressure and absolute temperature at any altitude. The derivation of (2) is given by Callahan [CALLAHAN and Others, 1951].

The q due to cosmic-ray energy was computed from the curves published by MONTGOMERY [1949]. All data were reduced to standard temperature and pressure.

The results are shown in Table 1. In columns (6), (7), (8), and (9) are listed the values of measured λ_-, of α, which is a function of pressure and temperature, and of q_λ and q_c. The term q_λ was computed from the measurement of λ_-, and q_c was derived from the cosmic-ray curves. Considering the uncertainty involved in obtaining data from the cosmic-ray curves, one can state that agreement between q_c and q_λ is good. It is to be noted that values of q_λ are larger. This should be so. It must be remembered that the measurement of conductivity represents the total ionization within a specified volume of air, whereas some of the softer components are not included in q_c.

Table 1--Rate of ion production

Geomagnetic Latitude (1)	Altitude (2)	Pressure (observed) (3)	Temperature (4)	Temperature (5)	λ_- (6)	α (7)	$q_\lambda{}^a$ (8)	$q_c{}^a$ (9)
°	km	mm Hg	°C	°K	statmho/cm			
45	6.4	335	-18	255	11.7×10^{-4}	1.79×10^{-6}	42.4	33.8
22			-10	263	9.6×10^{-4}	1.79×10^{-6}	25.0	22.6
45	5.2	496	-14	259	8.15×10^{-4}	2.09×10^{-6}	32.9	21.2
22			- 4	269	7.05×10^{-4}	2.09×10^{-6}	20.8	14.9
45	3.8	657	- 4	269	5.5×10^{-4}	2.21×10^{-6}	17.8	14.0
22			+ 6	279	5.2×10^{-4}	2.21×10^{-6}	13.4	9.35

[a] Expressed in ion pairs/sec-cm^3, reduced to standard temperature and pressure; q_λ is the value computed from conductivity data; q_c is the value computed from cosmic-ray data.

Conclusions--The computed values of q obtained from conductivity measurements over the Pacific Ocean in the geomagnetic latitude range of 22° and 45°N agree well with earlier values of q [BOWEN and Others, 1938] taking into account the possible errors in measurements and the statistical fluctuation in the parameter measurement.

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THE AREAL DISTRIBUTION OF GEOMAGNETIC ACTIVITY AS AN AEROMAGNETIC SURVEY PROBLEM NEAR THE AURORAL ZONE

L. W. Morley

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of Mines and Technical Surveys, Ottawa)

Abstract--Aeromagnetic surveying within the auroral zone is complicated by the high incidence of severe magnetic disturbance. Although corrections for the time variations could be made by means of data obtained from a ground station located centrally within the survey area, the areal extent over which such corrections would be valid is not known. The paper gives magnetic-disturbance data obtained from two simultaneously operated ground stations, placed initially 130 mi apart (209 km), and later 87 mi (140 km) apart, within the auroral zone. It is found that such corrections would be seriously in error for separations of this order between ground and air stations.

Introduction--Near the auroral zone, the high incidence of geomagnetic activity may seriously hamper airborne magnetic surveys, for which the available operating time is limited in any case. Table 1 illustrates for two geomagnetic latitudes the extent of such interference. This table is based on records obtained at the Dominion Observatory's magnetic observatories at Baker Lake (Northwest Territories) and Meanook (Alberta). A three-hourly range not exceeding 300γ ($1\gamma = 10^{-5}$ oersted) was chosen as the criterion for an acceptably quiet day. It is indicated by these data that there would be enough quiet periods to conduct an aeromagnetic survey (without very serious loss of flying time) at the geomagnetic latitude of Meanook, but not at that of Baker Lake.

Table 1--Number of days when magnetic storms would have seriously impaired the accuracy of aeromagnetic surveys conducted in the vicinity of these stations

Date	Meanook[a]	Baker Lake[b]
June 1950	2	Information
July 1950	4	not
Aug. 1950	3	available
June 1951	2	28
July 1951	2	24
Aug. 1951	6	11 (out of 11)[c]
June 1952	7	26
July 1952	7	31
Aug. 1952	2	26

[a] Latitude 54°35′ N., longitude 113°40′ W., geomagnetic lat. 61.8°.

[b] Latitude 64°20′ N., longitude 96°00′ W., geomagnetic lat. 73.5°.

[c] Station was out of operation for remainder of month.

For aeromagnetic surveys in latitudes of very frequent magnetic disturbance, consideration has been given to the possibility of surveying during magnetic storms and correcting the records by using data obtained from a ground station located centrally within the survey area. In such a scheme, the mechanics of synchronizing the air and ground stations are relatively simple. The validity of such corrections is still doubtful, however, when the survey aircraft is at distances of the order of 100 mi (160 km) from the controlling ground station. It was in an attempt to assess this validity that the observations described in this paper were made.

Methods of observation--Two saturable-core total field magnetic airborne detectors (MAD) were operated on the ground for a total of 25 days (see Fig. 1). In the first set-up, used from September 23, 1952, until September 30, one instrument was operated at McMurray, Alberta, while the other was operated at Lac la Biche. In the second set-up, maintained from October 8 until October 22, one was stationed at Lac la Biche while the other was at Smith.

Operation was suspended each morning between 02h 00m and 07h 00m because of a shortage of personnel.

Figure 2 shows the three-hourly K indices for the period September 23 to October 22, 1952, illustrating general magnetic storminess prevailing during the observations. The magnetometer

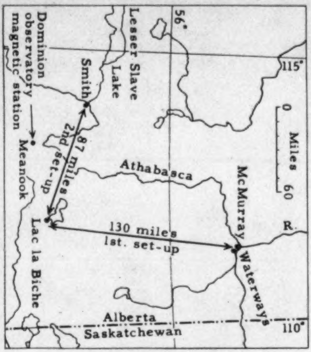


Fig. 1--Sketch map showing locations of observation points

recorders were run at a chart speed of six in/min (15 cm/min) throughout the operation. This speed proved to be excessive, as the shortest period of disturbance observed with this equipment was five seconds. A chart speed of one inch per minute would have been sufficient.

Esterline Angus recorders with spring-driven chart feeds were used. Time marks were made on the charts every five minutes, using time signals received from radio station WWV at Washington, D. C. During those hours when reception was so poor that no time signals could be received, reference was made to rated chronometers. It is considered that corresponding magnetograms of the two stations could be synchronized to within one second.

Results--Data from both stations were plotted against GMT on a single graph paper. This facilitated comparison of the two traces.

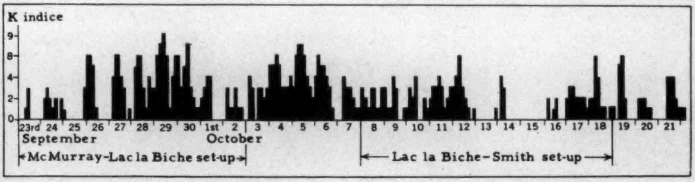
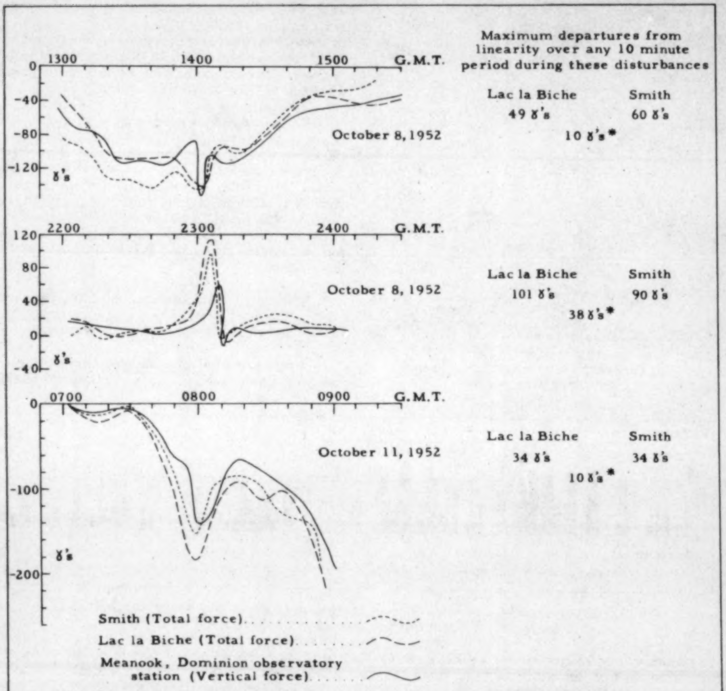


Fig. 2--Three-hourly K indices for the Dominion Observatory Magnetic Station at Meanook, Alberta, during period of observations, 1952

It was expected that the phases and amplitudes of disturbances observed simultaneously at stations of such separations would be nearly identical, but this was not found to be the case. The general shapes of the corresponding disburbance curves were, however, similar. Figures 3 and 4, which are smoothed versions of some of the disturbance records depicted on the same time scale, illustrate this. Certainly it was found that when conditions were disturbed at one location, they were also disturbed at the other location. Similarly, quiet conditions at one station corresponded to quiet conditions at the other.

Figures 3 and 4 also illustrate what was found to be generally true, namely, that there was better agreement between the curves from Lac la Biche and Smith, which are 87 mi (140 km) apart in an east-west direction, than there was between those of McMurray and Lac la Biche, which are 130 mi (209 km) apart in a north-south direction. It is not known whether this is due to the greater distance between the two latter stations or to the fact that they are in a north-south line rather than an east-west line.

The lack of correspondence between stations represented by the curves in Figures 3 and 4 appears very large when viewed with the idea of using data from one ground station to correct an aeromagnetic record obtained over the other station. In compilation of aeromagnetic data, however, the only assumption made about time variation of the Earth's field is that the disturbance curve does not depart from linearity during the time the aircraft is flying from one cross line to the next. Taking this time to be ten minutes, the maximum errors which would be incurred during the disturbances depicted in Figures 3 and 4 are tabulated to the right of the corresponding disturbance curves. Also tabulated are the errors which would result if one station were used to control a survey flown over the other station. It is significant that there is no appreciable lessening of these errors over those incurred if no ground control station were used at all and if linearity over ten minute periods was assumed.

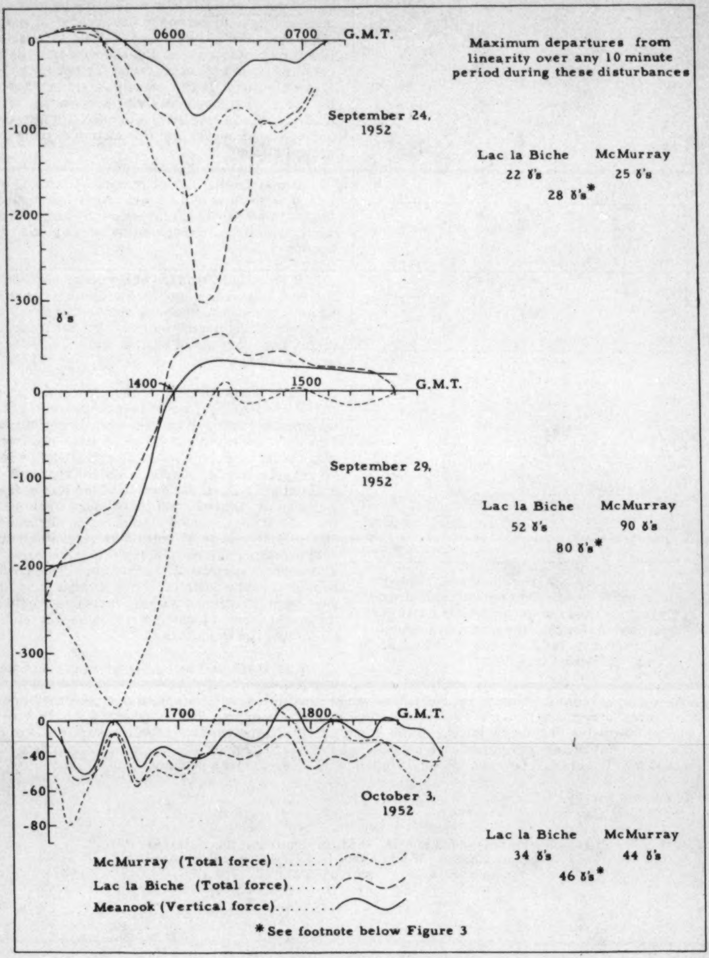


* Maximum divergences between the Smith and Lac la Biche records taken over any ten minute period during these disturbances. In measuring these divergences the curve from one station was transferred to tracing paper, laid over the corresponding curve from the other station and adjusted until the maximum divergence was at a minimum. These figures represent the approximate error that would be incurred if the record from one station were used to correct an aeromagnetic record obtained near the other station.

The departures from linearity over ten minute periods represent the approximate errors that would be incurred if no ground control station were used

Fig. 3--Comparison of magnetic disturbances (smoothed records)

Before proceeding to draw conclusions concerning the problem in hand, a few observations about the behavior of micropulsations are presented in Figure 5. A clear-cut case of phase reversal is shown in Figure 5a for the north-south set up; but no instance of such reversal was observed in the east-west set-up of Lac la Biche and Smith. Such a phenomenon could best be explained by an overhead electric current with an east-west path lying between the two stations. Slight phase displacements as illustrated in Figure 5b were observed for both set-ups. Such data might be used to calculate the velocity of propagation of these fluctuations. Figure 5c shows how some minor pulsations appearing on one trace are absent on the other. This was a condition observed during large disturbances only, and would seem to indicate that not all these currents travel in an east-west direction. Some major disturbances were accompanied by these micropulsations while as



Maximum departures from linearity over any 10 minute period during these disturbances

Lac la Biche 22 δ's McMurray 25 δ's
28 δ's*

Lac la Biche 52 δ's McMurray 90 δ's
80 δ's*

Lac la Biche 34 δ's McMurray 44 δ's
46 δ's*

McMurray (Total force)........

Lac la Biche (Total force)......

Meanook (Vertical force)........

*See footnote below Figure 3

Fig. 4--Comparison of magnetic records

many were not. Pulsations were considerably more frequent during violent storms than on moderately stormy days.

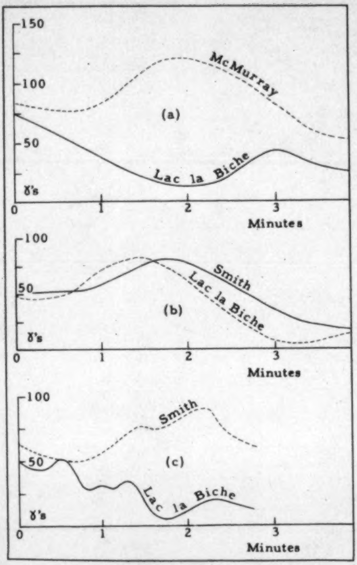


Fig. 5--Examples from magnetic records; (a) phase reversal in north-south direction; (b) phase displacement in east-west direction; (c) the different character of disturbances between stations 87 mi apart in an east-west direction

Conclusions--If it is necessary to conduct an aeromagnetic survey in the auroral zone during a magnetic storm, there is little to be gained in attempting to correct the records using data obtained from a ground station farther than 87 mi (140 km) away. Better control might be expected for closer distances but flying economy is seriously reduced if the aircraft cannot fly farther away than 35 mi (56 km) (for example) from the ground station.

It may be that closer correspondence is obtained between storm patterns for greater distances in an east-west direction than in a north-south direction, although this was not proved with certainty.

If the usual standard of accuracy required for aeromagnetic maps were somewhat relaxed, useful information could be obtained over shield areas by flying during storms. Such inaccurate maps, however, would be of doubtful value for oil survey work.

In order to investigate the problem in hand more thoroughly, it would be necessary to set up a north-south and an east-west line of simultaneously operated and closely spaced observation stations. Such a procedure, however, would be very costly. A more economical approach was suggested by C. H. M. Turner of the Radio Physics Laboratory, Ottawa. This procedure would be to fly away from a ground station out to distances of 100 mi (160 km) in an amphibian aircraft equipped with a magnetometer, landing every ten miles or so for short periods of observation. This could be done in a north-south direction as well as in an east-west direction. Such a procedure should indicate the range at which disturbance curves begin to diverge in pattern.

It is suggested that a magnetic gradiometer which measures the difference in total field strengths between two closely spaced points would provide a practical solution to the problem of conducting aeromagnetic surveys during severe magnetic storms. Such a system would be virtually insensitive to time variations of the Earth's field. If the vertical gradient were measured, it may be that better correspondence between near-surface geology and magnetics might be obtained than is obtained between the total field and the near-surface geology.

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THE EFFECT OF WIND ON NIGHTTIME RADIATIONAL COOLING

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Abstract--Results obtained by Brunt, Frost, Jaeger, and Knighting are briefly reviewed, and it is shown that the exact results of Jaeger and Knighting are closely duplicated by a much simpler expression obtained primarily through use of two simplifying assumptions: (1) A finite depth of modification of the lower layers of the atmosphere is assumed which increases through the night and below which heat flux is constant with height. (2) Starting at sunset, the diffusive flux of heat from the soil and from the lower atmosphere is constant through the night. The expression is compared with experimental data obtained by the University of Texas, and it is found to yield results which agree well with observation in the absence of such complicating factors as cloudiness and condensation.

Historical development--The first important work in this field was done by BRUNT [1939] who assumed that the flux of heat from the soil was constant through the night and equal to the net outgoing radiation R_N.

With these assumptions, the problem becomes simply a solution of the heat equation

$$dT/dt = k_1 \partial^2 T/\partial z^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

which may be found in most standard physics texts. Thus, assuming all the heat lost is provided by the soil, and taking

$$(\rho_1 c_1 k_1 \partial T/\partial z)_{z=o} = R_N = \text{constant}$$

Brunt obtains

$$f_o = - 2 R_N t^{1/2}/\rho_1 c_1 (k_1 \pi)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where

f_o	fall in temperature at the Earth's surface (z = 0) after time t, where t = 0 as night begins
R_N	net loss in heat from air-soil interface by nocturnal radiation
ρ_1	apparent soil density
c_1	specific heat of the soil
k_1	soil diffusivity
T	temperature of the soil

However, it is obvious that the air also supplies heat included in the net outgoing flux. FROST [1948], therefore, solved the Fick equation (Eq. 3 below) for diffusion in the atmosphere assuming that the flux of heat downward to the Earth's surface was constant through the night and equal to R_N. He thus assumes all the heat to come from the air and solves the equation

$$\partial\theta/\partial t = \partial(K \partial\theta/\partial z)/\partial z \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

with the boundary condition

$$(\rho c_p K \partial\theta/\partial z)_{z=o} = R_N = \text{constant}$$

and obtains

$$f_o = - R_N [(m + 1)^2 \, a t]^{m/1+m} / a m c_p \rho \Gamma [1/(m + 1)] \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (4)$$

where

a	meteorological parameter containing wind speed and surface roughness (under radiation conditions a ≅ 25 for England in summer according to KNIGHTING [1950], while Frost estimates a ≅ 40)
K	eddy diffusivity, according to Frost equal to $a z^{1-m}$
m	index of the assumed power-law profile
θ	potential temperature in the air, obeying a power-law distribution with height and a function of both t and z
c_p	specific heat of the air
ρ	density of the air

Recognizing that both the atmosphere and soil may provide heat to maintain R_N, however, JAEGER [1945] and KNIGHTING [1950] have solved equations (1) and (3) together with the boundary conditions

$$\theta = T \quad \text{for} \quad z = o, t > o$$

$$F_A + F_S = R_N \quad \text{for} \quad z = o, t > o$$

where

F_A flux (air) = $- (a \rho c_p z^{1-m} \partial\theta/\partial z)_{z=o}$

F_S flux (soil) = $- (\rho_1 c_1 k_1 \partial T/\partial z)_{z=o}$

Objections to previous solutions--(1) Unfortunately, the solutions of both Knighting and Jaeger are rather involved and become quite laborious when applied to a practical problem. Jaeger's solution is in terms of a series which, if it converges at all, generally does so rather slowly. Knighting's solution, on the other hand, involves a definite integral which must be evaluated numerically. (2) Jaeger's series solution quickly becomes divergent as wind speed is increased. (That is, "a" increasing and "m" decreasing [FROST, 1946].) Knighting's solution, on the other hand, applies only to the special case of m = 1/3, and it is doubtful if a more general solution can be written in usable form. Thus, while they are very useful in appraising the adequacy of simplifying approximations, they both appear to be restricted to a narrow range of wind speed and stability conditions. (3) The solutions of both Knighting and Jaeger assume a power-law distribution for both wind and temperature. However, a recent empirical law deduced by DEACON [1949], which reduces to a logarithmic profile in the case of neutral equilibrium, appears more adequately to fit observation. It is to be noted that, with the usual power-law profile, the effects of both stability and surface roughness are apparently reflected in the profile index, m, in a very complicated way; thus, the separation of the two factors in the Deacon law, if complete, is very important. Indeed, it is this probable characteristic of the Deacon theory that makes our present goal a reasonable one, since it allows us to uniquely relate the Deacon profile index, β, to stability as defined by some parameter equivalent to Richardson's number (see Fig. 1).

The present approach--In the absence of condensation, our basic assumptions are as follows: (1) To a first approximation, we take F_S = constant (Brunt's assumption) and F_A = constant (Frost's assumption) when integrating with respect to time. Like Knighting and Jaeger, we assume $F_S + F_A = R_N$ = constant. (2) In order to use the Deacon law for the distribution of meteorological parameters with height, we assume that the flux of heat is constant with elevation below a certain finite height of penetration, $\delta(t)$, to which modification has extended, and zero above. It will be shown that $\delta(t)$, while it does not actually exist as such, is a very convenient fiction.

Now let us take θ_i to be the initial potential temperature of the air before noctural modification begins. At a time t = 0, usually occurring shortly before sunset, we assume the initial condition, $\theta_z = \theta_i$ = constant. Next, consider a cylinder of unit cross-sectional area extending from $z = z_o$ to $z = \delta(t)$. (For the best interpretation of z_o as used here, see the brief development of the Deacon boundary-layer theory in the appendix.) Then, the total heat lost from the cylinder since time t = 0 is

$$H = \int_{z_o}^{\delta(t)} \rho c_p \, (\theta_\delta - \theta_z) \, dz$$

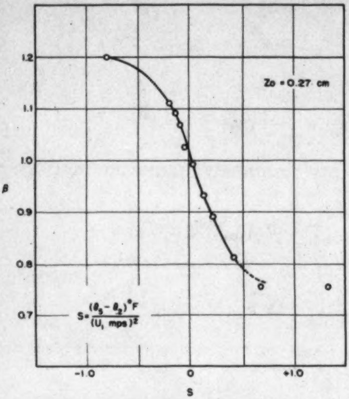

Fig. 1--The variation of β with stability after DEACON [1949]

and the flux of heat out of the cylinder is given by

$$dH/dt = F_A = (d/dt)\int_{z_0}^{\delta(t)} \rho c_p (\theta_\delta - \theta_z)\, dz \ldots (5)$$

Since we have assumed the Deacon law to be the most generally acceptable expression for diffusive flux in the lowest layers of the atmosphere, we have for the Earth's immediate boundary layer (see appendix)

$$F_A = \rho c_p k_0 U_* (\theta_z - \theta_0)(1 - \beta) / [(z/z_0)^{1-\beta} - 1] \ldots\ldots\ldots\ldots (6)$$

where

U_*	$\sqrt{\tau_0/\rho}$, the so-called friction velocity, which may be obtained from Eq. (14), derived in the appendix
τ_0	shearing stress at $z = 0$, and assumed independent of height in the boundary layer
β	profile index ($\beta > 1$ unstable, $\beta < 1$ stable)
k_0	von Karman's constant ($\cong 0.40$)

Table 1--Roughness parameter for various typical surfaces

Surface	z_0
	cm
Mud flats, smooth ice	0.001
Sun-baked sandy alluvium (level desert, India)	0.03
Sand	0.04 - 0.06
Lawn (1 cm grass length)	0.10
Lawn (1.5 cm grass length)	0.20
Natural snow surface	0.20 - 0.50
Lawn (3 cm grass length)	0.60 - 0.80
Lawn (5 cm grass length)	1.0 - 2.0
Downland (winter)	1.0 - 2.0
Fallow land	2.0 - 3.0
Russian steppe	2.0 - 3.0
Downland (summer)	2.0 - 4.0
Open grass land	3.0 - 4.0
Long grass (60 - 70 cm length)	4.0 - 9.0
Wheat field	4.5
Turnip field	6.5
Fully grown root crops	14.0

z_0	roughness parameter with dimensions of length and may be obtained experimentally from measured wind profiles at a given station, or may be estimated from Table 1
θ_0	potential temperature of the air at $z = z_0$

Since we have assumed that F_A is relatively stationary in time compared to θ, and since ρc_p is essentially constant through our height range, we have

$$\rho c_p \int_{z_0}^{\delta(t)} (\theta_\delta - \theta_z)\, dz = F_A\, t$$

For simplicity in mathematical manipulation, let us define

$$f_o = \theta_o - \theta_\delta = \theta_o - \theta_i$$

$$f = \theta_o - \theta_z$$

and thus write

$$\rho c_p \int_{z_o}^{\delta(t)} f_o \, (1 - f/f_o) \, dz = - F_A t$$

If we assume for a moment that the boundary layer profiles may be extrapolated up to the height $\delta(t)$, we have from (6)

$$\rho c_p f_o \int_{z_o}^{\delta(t)} \left\{ 1 - [(z/z_o)^{1-\beta} - 1]/[(\delta/z_o)^{1-\beta} - 1] \right\} dz = - F_A t$$

which integrates to

$$[1 + (1 - \beta)(\delta/z_o)^{2-\beta} - (2 - \beta)(\delta/z_o)^{1-\beta}]/(2 - \beta)[(\delta/z_o)^{1-\beta} - 1] = - F_A t/\rho c_p z_o \quad \ldots\ldots\ldots (7)$$

Now let us arbitrarily assume that (6), the expression for flux, applies all the way to the fictitious height $\delta(t)$ at which $\theta(z) = \theta_i = \theta_\delta$ (or $f = f_o$). We may obtain an expression for f_o as a function of t and F_A as follows:

Combining (6) and (7) we have

$$1 + (1 - \beta)(\delta/z_o)^{2-\beta} - (2 - \beta)(\delta/z_o)^{1-\beta} = (1 - \beta)(2 - \beta) \, k_o U_* t \, z_o^{-1}$$

But since

$$(1 - \beta)(\delta/z_o)^{2-\beta} >> (2 - \beta)(\delta/z_o)^{1-\beta} - 1$$

except during the early part of the first hour of the night, we have essentially

$$\delta = [(2 - \beta) \, k_o U_* z_o^{1-\beta}]^{1/(2-\beta)} \, t^{1/(2-\beta)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

and

$$(\delta/z_o)^{1-\beta} - 1 = [(2 - \beta)(k_o U_*/z_o) t]^{(1-\beta)/(2-\beta)} - 1$$

So from equation (6)

$$f_o = - [\{(2 - \beta)(k_o U_*/z_o) t\}^{(1-\beta)/(2-\beta)} - 1] \, F_A/(1 - \beta) \, \rho c_p k_o U_*$$

Now since $F_A + F_S = R_N$ and since from (1) we have

$$F_S = - \rho_1 c_1 \sqrt{k_1 \pi} \, f_o/2 \sqrt{t}$$

we get finally

$$\begin{aligned} f_o = - R_N [& \rho_1 c_1 \sqrt{k_1 \pi}/2 \sqrt{t} \\ & + \rho c_p k_o (1 - \beta) U_*/\{[k_o U_* (2 - \beta)/z_o]^{(1-\beta)/(2-\beta)} \, t^{(1-\beta)/(2-\beta)} - 1\}]^{-1} \quad \ldots\ldots\ldots (9) \end{aligned}$$

According to our original assumptions, we may proceed a step further and write

$$\theta(z,t) = \theta_i + f_o \, [(\delta^{1-\beta} - z^{1-\beta})/(\delta^{1-\beta} - z_o^{1-\beta})] \quad \text{for } z < \delta(t) \quad \ldots\ldots\ldots (10)$$

and $\theta(z, t) = \theta_i$ for $z > \delta(t)$.

Thus, if z is taken as the instrument shelter height and $\theta(z, t)$ the temperature at this height, or using (8) we have an expression for θ_s, the shelter temperature.

Considerable caution should be exercised when using (10) for predicting temperature profiles to any great height, since the assumption that F_A is constant with elevation implicit in (6) is strictly applicable only in the atmospheric boundary layer. However, we have assumed as a first approximation that (6) applies all the way to the fictitious height $\delta(t)$, and while we will show this approximation to be quite adequate as far as f_o is concerned, one would expect the temperature profile, which is directly affected, to show a considerable departure from observation at any considerable elevation. Surprisingly enough, when profiles computed from (10) are compared with those observed at Manor, Texas [GERHARDT and Collaborators, 1950], the agreement is rather good except during the very first hours of the night. The comparison is rather unsatisfactory, however, because the difficulty of deciding on the appropriate initial conditions tends to obscure other possible discrepancies during these early hours. In addition, the Manor observations extend only to 288 ft, while $\delta(t)$ is usually much greater in the later hours.

Evaluation of basic assumptions--It is important to note that we have assumed the fluxes from soil and air to be independent of time when performing the integrations. This is of primary importance in simplifying the form of the expression for f_o. For example, it permits a direct combination of Brunt's and Frost's formulas which may then be compared with the more rigorously correct formula of Jaeger. To obtain the order of difference to be expected between the two expressions, it may be worthwhile to work out the problem used as an example by Brunt, Frost, and Knighting, and compare results directly. They assumed the following values in cgs units for the meteorological and soil parameters on an average June night in England: $\rho_1 = 2.5$, $c_1 = 0.20$, $k_1 = 4.7\times10^{-3}$, $a = 40$, $m = 1/3$, $R_N = 2.1\times10^{-3}$, $c_p = 0.24$, $t = 7$ hr, $\rho = 1.28\times10^{-3}$.

For these values Brunt gets $f_o = -11°C$, Frost gives $f_o = -15.8°C$, and Knighting finds $f_o = -6.3°C$. Using Jaeger's series solution, we obtain $f_o = -6.5°C$. (Since Jaeger's and Knighting's solutions should agree for a given set of conditions, it seems likely that Knighting used a slightly different value for one of the parameters we have listed above.)

The corresponding solution obtained by assuming that the fluxes from soil and air are constant in the first approximation gives $f_o = -6.40°C$. Since the departure from the rigorous result is even less for smaller t, the approximation is entirely adequate for this problem. The difficulty in obtaining a solution at high wind speed by either Knighting's or Jaeger's formula makes it impossible to thoroughly check our approximation under these conditions. Qualitatively, however, we might predict the agreement to remain about the same, since for high wind speed the approximation gets better for the atmospheric medium and worse for the soil medium. Simultaneously, however, the contribution from the soil becomes less important relative to that from the atmosphere.

In order to make use of the convenient Deacon equation, we made another major approximation in (9) by assuming that equilibrium conditions have been reached below the height $\delta(t)$, and that the flux is constant across all z planes for $z < \delta(t)$. From this approximation it is to be expected that the profiles derived will be somewhat in error, but we might anticipate that f_o should be little affected. Indeed, using the above approximation but assuming a power-law profile for purposes of comparison, a formula corresponding directly to Frost's, (Eq. 4), may be obtained. Thus we find

$$f_o = -R_N\left[(m+1)^2\, a t\right]^{m/(1+m)} / a m c_p \rho \left[1/(m+1)\right]^{-m/(1+m)}$$

It is seen that the functional form is the same as (4) and that the corresponding f_o's only differ by the ratio of $[1/(m+1)]^{-m/(1+m)}$ to $\Gamma[1/(m+1)]$. This introduces a maximum error of about three-tenths of a degree in our final expression for f_o during a seven-hour night. In view of the doubtful numerical value of k_o (variously estimated at from 0.38 to 0.45), and the difficulty of accurately measuring z_o, this difference would appear to be quite negligible. In fact, it is entirely possible that semi-empirical determination of the best values of both $\rho_1 c_1 \sqrt{k_1 \pi}/2$ and k_o/z_o will be found most practical for any given station due to the usually non-uniform character of soil and terrain.

Verification of theoretical results--The measurements taken by the University of Texas at Manor, Texas [GERHARDT and Collaborators, 1950], appear to offer the best available data for experimental verification of the above theoretical results. (In the course of reviewing this paper it was called to the author's attention that another body of data taken by Johns Hopkins University is also exceptionally well suited for verification.) Five runs were made by the Texas workers. The three clear nights on which the data were sufficiently complete for our purposes were December 19-20, 1949, and February 22-23 and 23-24, 1950. In Figures 2, 3, and 4, the observed fall in temperature after sunset at an elevation of five feet (ΔT_5) is shown plotted with the theoretical fall for various wind speeds.

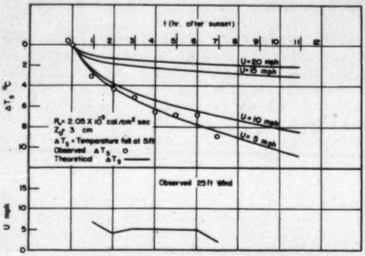

Fig. 2--Relationship of observed to computed temperature fall after sunset, Manor, Texas, February 22-23, 1950

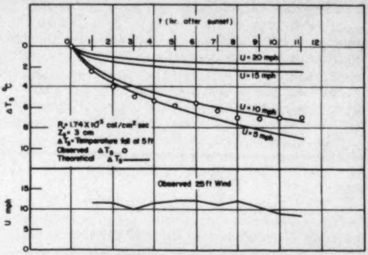

Fig. 3--Relationship of observed to computed temperature fall after sunset, Manor, Texas, February 23-24, 1950

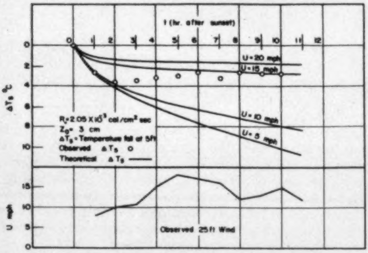

Fig. 4--Relationship of observed to computed temperature fall after sunset, Manor, Texas, December 19-20, 1949

The net outgoing radiation, R_N, was obtained from the Elsasser radiation diagram, using the appropriate 2100 San Antonio raob. The roughness parameter used (three cm) is that obtained by the University of Texas workers for the month of February [GERHARDT and JEHN, 1950]. The soil parameters found by the University of Texas for this region are, in cgs units: $\rho_1 = 1.8$, $c_1 = 0.33$. For soil diffusivity, we have assumed $k_1 = 2.0 \times 10^{-3}$, a value given by KEEN [1931] for fine, sandy, dry loam.

Since very low wind velocities were often observed at one meter, we have adapted Deacon's stability criterion, S (Fig. 1), to wind and temperature measurements made at 25 ft (see appendix).

It is seen that the agreement between theoretical and observed values of ΔT_5 is quite satisfactory in Figures 2 and 4. In Figure 3, the observed values are somewhat greater than the computed values for the observed wind speed. However, if we had used the same value of R_N on the night of February 23-24, as was used on February 22-23, near perfect agreement would have been noted. It, therefore, seems worthwhile to examine the adequacy of the 2100 San Antonio raob for the night in question. Going to the midnight surface map for February 23-24, we see that warm, moist Gulf air is spreading northward over southern Texas. Significantly, the midnight map shows San Antonio to be definitely under the influence of this moist-air advection with an increase in relative humidity of about ten per cent over the previous night. At Manor, on the other hand, the relative humidity has actually decreased, and if we apply Brunt's approximate formula for obtaining R_N from surface data, $R_N = \sigma T^4 (0.40 - 0.042 \sqrt{e})$, where T = temperature in degrees absolute, e = vapour pressure in millibars, we get the same value for R_N at Manor on both nights in question. Thus, it seems that, indeed, the value of R_N used for February 22-23 is representative of the following night also. For the sake of consistency, however, we have chosen to use the value indicated by the 2100 San Antonio raob in all three cases. In Figure 2 we have not included observed values after 0300 because katabatic effects became obvious as indicated by Table 2, extracted from GERHARDT and Collaborators [1950].

Appendix

The Deacon law--The distribution of wind velocity with elevation was found by DEACON [1949] to fit the expression

$$du/dz = b\, z^{-\beta} \quad \text{. . . . .} \quad (11)$$

Table 2--Winds in a katabatic drifting situation, early morning of February 23, 1949, Manor, Texas

Height above surface	Time, six-minute periods beginning at							
	00h 30m	01h 00m	01h 30m	02h 00m	02h 30m	03h 00m	03h 30m	04h 00m
ft	Wind direction (degrees from north) and wind speed (mi/hr)							
307	[a] - 2	[a] - calm	[a] - calm	[a] - calm	[a] - calm	[a] - calm	[a] - calm	[a] - calm
181	70 - 6	71 - 3	79 - 2	[b] [b]	79 - 2	[b] - calm	[b] - calm	[b] - calm
91	47 - 4	45 - 4	44 - 3	49 - 1	51 - 1	[b] - calm	[b] - calm	[b] - calm
41	[b] - calm	35 - 2	34 - 3	29 - 2	29 - 2	[b] - calm	[b] - calm	[b] - calm
12	[b] - calm	[b] - calm	350 - 3	350 - 3	350 - 4	334 - 2	324 - 3	305 - 4
3	[b] - calm	[b] - calm	[b] - calm	[b] - calm	[b] - calm	[b] - calm	[b] - calm	[b] - calm

[a]Values missing. [b]Not representative.

Integrating (11) with the condition that $u = 0$ at $z = z_o$, we have

$$u_z = [b z_o^{1-\beta}/(1-\beta)][(z/z_o)^{1-\beta} - 1] \ldots\ldots\ldots\ldots (12)$$

Expanding this expression in a power series and demanding that it approach the classical logarithmic expression

$$u_z = (U_*/k_o) \log_e z/z_o \quad \text{as } \beta \rightarrow 1.0$$

Deacon obtains the value of b as

$$b = U_*/k_o z_o^{1-\beta} \ldots\ldots\ldots\ldots (13)$$

So, from (12) and (13), we may write

$$U_* = \left\{k_o (1-\beta)/[(z/z_o)^{1-\beta} - 1]\right\} u_z \ldots\ldots\ldots\ldots (14)$$

and from the definition of eddy diffusivity, we see that

$$K = U_*^2/(du/dz) = k_o U_* z_o^{1-\beta} z^{\beta}$$

DEACON [1949] and PASQUILL [1949] find that the temperature distribution, like the velocity distribution, may be represented by an expression similar to (11) and that the index, β, is approximately the same in both cases.

Finally, assuming that the eddy diffusivity coefficient is the same for both temperature and wind, we have

$$\text{Flux}(\theta) = \rho c_p K \partial\theta/\partial z = \rho c_p k_o u_* z_o^{1-\beta} z^{\beta} \partial\theta/\partial z$$

which integrates to (6) for the region in which flux is essentially constant with height.

Deacon's careful experiments indicate that β varies with stability as shown in Figure 1, where S is defined as

$$S = (\theta_5 - \theta_{0.2})/u_1^2$$

the height subscripts indicating meters and θ representing degrees Fahrenheit. It can be shown that for a given set of conditions, Richardson's number, which is the usual stability criterion, is determined uniquely by S.

If we assume the same value of β for wind and temperature and assume it also to be a function of stability only, the curve in Figure 1 may be expressed in terms of any convenient instrument heights and any given surface roughness.

However, probably a better relationship between β and stability is to be found in the theoretical approach of LAKE [1952], who relates the Deacon model to the theoretical model of Lettau. Lake thus obtains an analytical relationship between β and Richardson's number and in addition separates our roughness parameter into the two actually distinct effects of surface roughness and zero displacement of the neutral logarithmic profile.

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INTERNAL WAVES IN GEORGIA STRAIT

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Abstract--Wave-like patterns appearing on aerial photographs of Georgia Strait are interpreted as marking regions of intense surface roughness over the convergences associated with internal waves. The 16-ft tide of the Strait is suggested as the source of energy for the waves.

Introduction--Aerial photographs taken as part of an oceanographic survey of Georgia Strait waters adjacent to the City of Vancouver have revealed wave patterns of considerable size. One pattern, represented by Figure 1, shows a procession of great bands in striking contrast. Another group, farther to the northwest and shown by Figure 2, appears to consist of surface waves with crest to crest lengths as great as 3000 ft.

Geography and oceanography of the region--The Strait of Georgia, 120 nautical miles long by about 15 wide, is the main body of water separating Vancouver Island from the mainland (Fig. 3). It is connected to the ocean by narrower channels and inter-island passes leading to the Strait of

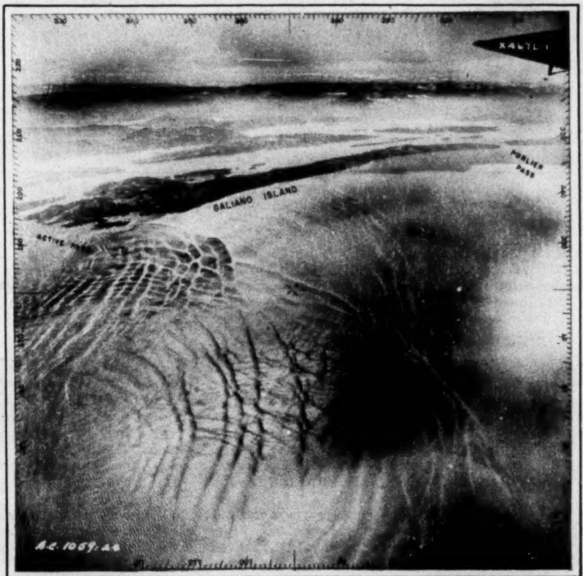


Fig. 1--Georgia Strait looking westward toward Galiano Island from the southern extremity of the line of flight; June 1, 1950 at 14h 35m; the boundary at the surface of a fresh-water front shows clearly this side of Porlier Pass

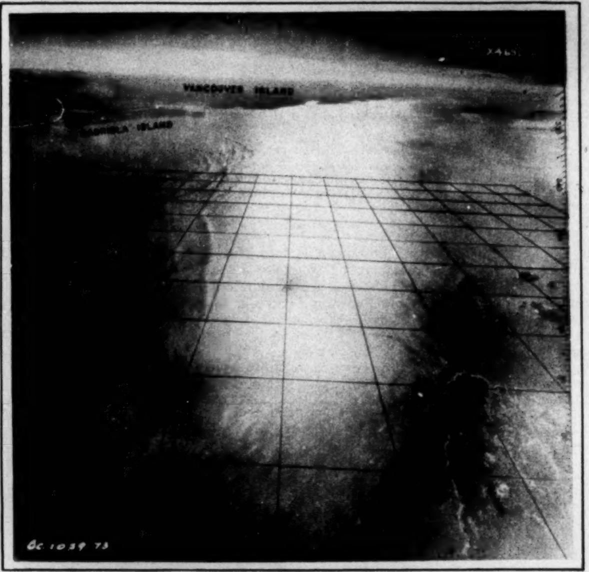


Fig. 2--Georgia Strait looking westward from the northern extremity of the line of flight; June 1, 1950 at 16h 18m; the grid divides the foreground area into square miles

Juan de Fuca in the south and Johnstone Strait in the north. In spite of its land-locked position, the flood and ebb of sea water through these passages permit a maximum tidal range of about 16 ft. Figure 4 illustrates typical curves for tropic and equatorial tides together with corresponding tidal currents in one of the connecting channels. In the region where these curves apply, the flood is generally toward the northwest and the ebb toward the southeast [CANADIAN HYDROGRAPHIC SERVICE, 1950].

The discharge of the Fraser River dominates southern Georgia Strait especially in late spring and early summer. During this season muddy fresh water in great volume fans out over clearer denser sea water yielding a distinctly stratified structure. The effect of the river on salinity distribution is illustrated for one particular period by Figure 5. As a rule when river flow is high, an upper brackish layer about ten feet deep ($S\ ^0/oo = 2$ to 20) is separated from a lower sea water layer ($S\ ^0/oo = 28$ to 30) by a transition zone about 10 to 30 ft thick. This structure is maintained by river discharge which continually replaces the upper layer and by tidal currents which tend to replace the sea water [PACIFIC OCEANOGRAPHIC GROUP, 1951].

Muddy water contrasts sharply with sea water and shows up lighter on photographs so that the degree of muddiness affords an approximate measure of the extent and direction of flow of fresh water. This property was utilized to investigate the movements of river discharge during varying stages of tide by a series of air photographs.

Aerial photography--A total of 1500 aerial photographs was taken in the vicinity of the Fraser River on two days, June 1 and June 10, 1950. Series of tri-camera overlapping views were obtained at two-hour intervals from 06h 00m to 18h 00m on June 1, during the fall and rise of a tropic tide, and similarly on June 10 during an equatorial tide cycle. The principal line of flight is indi-

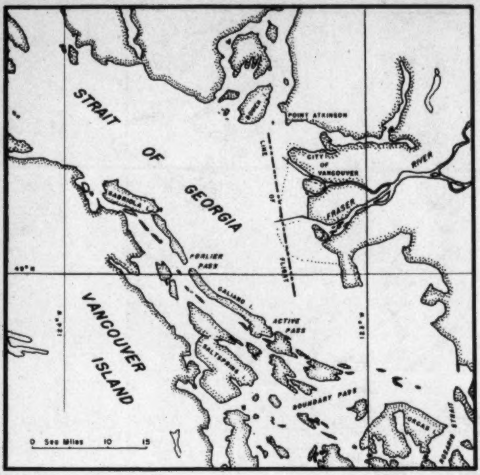

STRAIT OF GEORGIA
VANCOUVER ISLAND
GABRIOLA
PORLIER PASS
GALIANO I.
ACTIVE PASS
SALTSPRING
BOUNDARY PASS
ORCAS
ROSARIO STRAIT
BOWEN
POINT ATKINSON
CITY OF VANCOUVER
FRASER RIVER
LINE OF FLIGHT
49°N
124°W
123°W
0 Sea Miles 10 15

Fig. 3--Southern Georgia Strait; the line of flight for air photography is shown in its relation to the Fraser River and surrounding islands

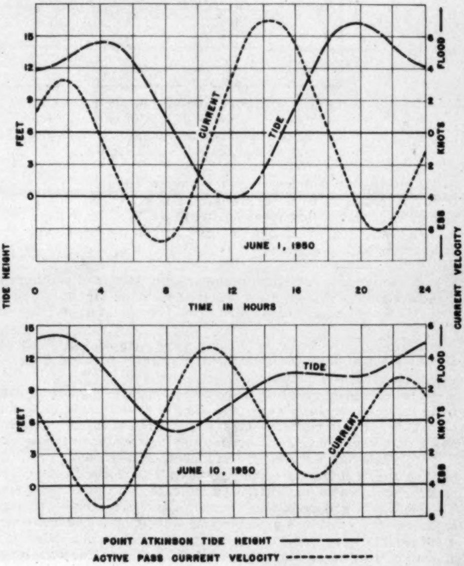
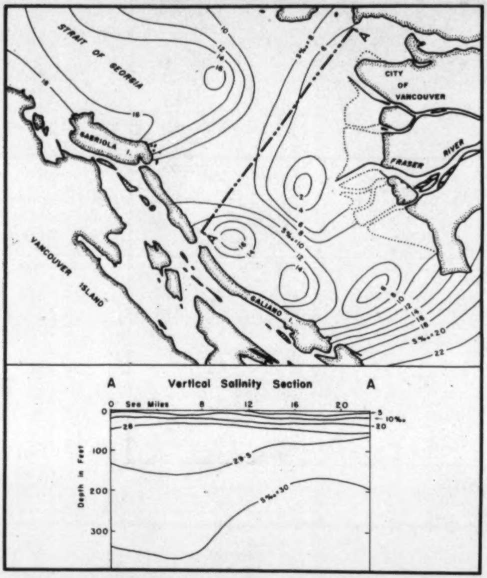


Fig. 4--Tide height at Point Atkinson with corresponding tidal currents at Active Pass, June 1 and 10, 1950


STRAIT OF GEORGIA
SABRIOLA I.
VANCOUVER ISLAND
GALIANO I.
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A
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2
4
6
8
S‰=10
12
14
16
8
10
12
14
16
18
S‰=20
22
A
Vertical Salinity Section
A
0 Sea Miles
8
12
16
20
Depth in Feet
0
100
200
300
28
29.5
S‰=30
5
10‰
20

Fig. 5--Salinity contours at six-foot depth in southern Georgia Strait, June 19-26, 1950; salinity stratification is shown in section (from data being studied by M. Waldichuk, Pacific Oceanographic Group, Nanaimo)

cated in Figure 3 and predicted tidal heights and currents are plotted in Figure 4. Wind on both occasions was generally northwest at ten to 20 mph but tended to be stronger on June 1. Both days were clear. River flow measured at Hope, B. C., two days before the photographs were taken, increased from 202,000 to 227,000 cfs between the two dates. These values represent about 80 pct of the river mouth discharge.

These surveys resulted in remarkable series of photographs showing successive positions of clouds of muddy Fraser River water in Georgia Strait. Four photographs have been selected as samples from among many which show prominent wave patterns.

Distinguishing features of large wave patterns--A study of the complete sequence of photographs yielded the following information which may aid in determining the nature and source of the prominent wave formations.

(1) In all photographs muddy water appeared lighter in tone than sea water. (Zones of glitter from reflected sunlight were of necessity discarded in this analysis.)

(2) Wave patterns were most pronounced in the two general regions represented by Figures 1 and 2 where they seemed to occur simultaneously but independently.

(3) These large waves are recorded in most photographs taken during periods of flood tide, but are absent in all taken during ebb-tide periods. Observations of the presence or absence of similar wave forms on other days indicate that this is a normal and not a particular phenomenon.

(4) Where groups of large wave forms have been photographed or observed, each has in general been preceded by a group having wavelengths one-third to one-half as great as those in the most prominent series. A significant feature which applies to these adjacent groups is that both appear to have begun abruptly with full amplitude and wavelength.

(5) Although the intensity of sunlight and the schedule of flights were similar on both dates, more numerous and distinct wave formations were recorded during the tropic tide series on June 1 than during the equatorial series on June 10.

(6) Well-defined wave patterns travelled in the same general direction as the flood tide. Some of them were simple wave trains (Fig. 2 and 6) while others showed interference patterns indicative of multiple sources, refraction or reflection (Figs. 1 and 7).

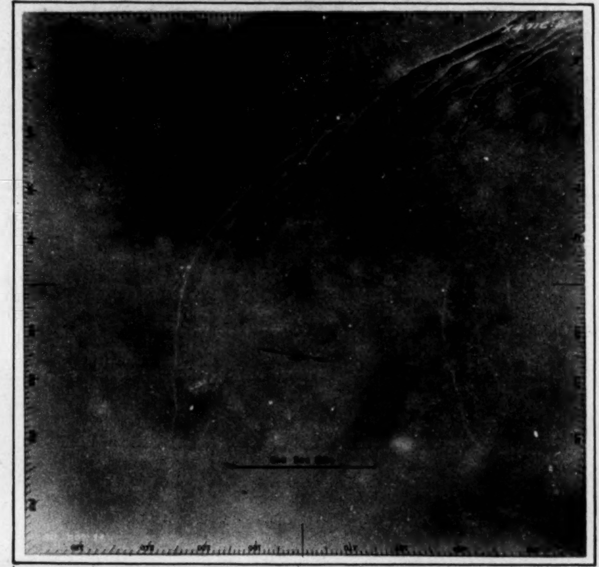

Fig. 6--Vertical photograph taken from southern end of line of flight; June 1, 1950 at 18h 09m; foam lines are shown extending from the ends of the narrow bands

(7) Measurements on the rate of progression of the wave group of Figure 2, which could be recognized in successive camera surveys, showed a speed of about one and a half knots. From this value some unknown velocity of tidal drift, perhaps half a knot, must almost certainly be subtracted.

(8) Alternate wide and narrow bands are the most prominent features which define the wave forms. Of these two, the narrow bands are more striking because they exhibit a line of sharp tone contrast along their length. In Figure 2 these give the appearance of impressive amplitude, but in Figure 1 the effect of wave height is less pronounced although contrasts are quite as sharp.

(9) Narrow bands in the central foreground of Figure 1 are predominantly dark but elsewhere in the photograph they are lighter than surrounding water.

(10) Foam lines, indicative of pronounced convergence, may be associated with narrow bands as they are in Figure 6, a vertical view.

(11) Surface waves generated by a consistent wind velocity were of the order of 80 ft from crest to crest. These were constant in magnitude and direction over the whole area and appeared to be unaltered in traversing regions dominated by the large wave forms.

(12) Close examination of the foreground of Figure 1 revealed what appear to be smaller surface waves which extend normal to the narrow bands. Similar waves are shown in greater detail by the enlarged vertical view of Figure 7 in which they average about 15 ft from crest to crest and appear to be unrelated to wind direction.

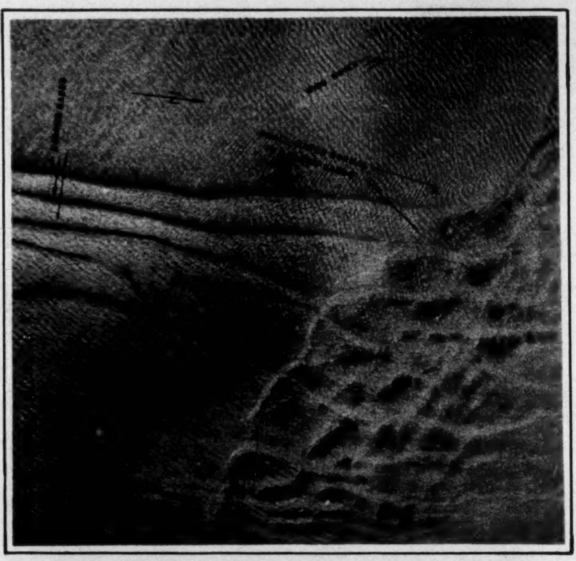

Fig. 7--Enlarged vertical photograph obtained at southern end of line of flight; June 10, 1950 at 12h 10m; small waves which extend normal to the narrow bands may be distinguished from the larger wind waves; the area shown is one square nautical mile

An interpretation of surface contrasts--The great waves of Figure 2 show the characteristic forms of light and shadow by which surface waves are normally perceived. If waves of this length had existed with even one foot of amplitude, they should have been recorded by the tide gage near Point Atkinson. If they were of lesser amplitude, it is most unlikely that they could have been photographed with such definition over a large area, especially in the presence of other higher surface waves. Because they lack evidence of appreciable height and because their length and speed do not correspond to those of surface waves, some other explanation must be sought not only for their presence but also for the property which permits them to be photographed.

One possible cause of contrasting reflectivity could be regular variations in mud content of surface water. In all photographs muddy water appears lighter in tone than clear water, yet narrow bands in the central foreground of Figure 1 appear dark while in other parts of the picture they appear lighter than surrounding water. Gradations in mud content are therefore not the cause of the reflectivity contrasts by which these large banded patterns are made visible.

The presence of small waves in the vicinity of narrow bands indicates that some disturbing force other than direct wind action prevails in this region. Disturbance of the water surface could occur along lines of convergence where waves, especially small ones, should be noticeably shortened and heightened. One frequently observes that small wind waves in the vicinity of tide lines, which by their accumulation of driftwood or seaweed mark convergence, are characterized by a shortness and steepness quite unlike surrounding waves. The presence of foam lines along some narrow bands as in Figure 6 suggests strongly that these mark lines of convergence. If this were true, then the area between narrow bands should be characterized by diverging water and should be relatively free of the small waves which contribute to surface roughness. Where water has an upward component of velocity, as it has on the windward side of a drifting ship, the resulting slick effectively inhibits the formation of small wind waves. Depending on the relative angles of Sun and camera, a roughened water surface may appear lighter or darker than an adjacent smooth area. Consider, for example, the familiar "cat's paws" formed when turbulent air is blown across a water surface forming capillary wind waves which may appear distinctly dark or may glitter brightly in the Sun. The gradations of light and shadow which define these banded patterns are believed to result from variations in the height, length, or shape of waves too small to be recognized in the photographs.

This interpretation of light and shaded areas and of the significance of the narrow bands is substantiated by observations from shipboard of regularly banded patterns under comparable wind conditions. Patterns observed consisted of elongated regions of short, choppy waves as much as three feet in height alternating with slicks.

Considering this evidence, it appears reasonable that the narrow bands recorded by the camera are regions of intense surface roughness resulting from converging water.

Banded patterns and related internal waves--If surface water converges and diverges along regularly recurring lines, then water below the surface must exhibit complementary horizontal and vertical components of flow. According to SVERDRUP and Others [1946, p. 588], this situation would exist if internal waves were present.

Suppose that a definite structure be assumed in order to make a first approximation of the speed of internal waves if they existed. Let an abrupt boundary separate an upper layer of water ten feet thick from a lower layer 1000 ft thick and let their densities be 1.00 and 1.02 respectively. Substituting these values into a formula for the approximate velocity of internal waves [SVERDRUP and Others, 1946, pp. 586-587] yields about 1.5 knot, a speed of the same order as that which has been measured. Thus the presence of internal waves is strongly indicated.

Probable cause of internal waves--Observations from shipboard left the impression that considerable energy must be supplied to a regularly banded pattern in order to maintain the turbulence apparent at the surface. Wind may build up a uniform system of gravity waves over the entire area, and perhaps part of this wave energy is expended in the form of visible turbulence; but in order to initiate a train of internal waves it is reasonable to look for some disturbing force and continuing source of energy supplied at the density boundary. The cyclic occurrence of large wave forms points to tide, in particular the flood tide entering from the southern passages, as the most important cause.

Energy is available in the hydraulic head of the Fraser River and in the rise and fall of tide. Utilization of a part of this energy in disturbing the density boundary may occur in one of the following ways.

TULLY [1952] has described the mechanics of a river discharging into the sea. He has shown that river discharge assumes the form of an expanding cloud of brackish water, or upper zone, which overrides a lower zone of denser sea water. Fresh water proceeding seaward has a relative velocity component opposite in direction to that of the deep water and thereby sets up a shear between the zones. A flooding tide which, because of its greater density, intrudes under the upper zone should similarly introduce shear between the water layers. This shear results in the formation of an intermediate or boundary zone characterized by considerable mixing. When the tide is flooding, the "front" of the fresh water cloud is marked by a line of convergence where surface waters, both fresh and salt, are carried downward into the boundary zone. Large turbulences which result in the violent displacement of water from one density medium to another may introduce vertical motion to the interface between density layers and thus initiate a train of internal waves. In southern Georgia Strait tidal currents can flood through connecting channels at velocities of several knots. Surface convergences resulting from these streams take the form of violent tide rips which are prevalent in this area. (Convergences referred to here involve a transfer of water from the surface to appreciable depths. Those associated with internal wave motion may not necessarily be accompanied by an actual downwelling of surface water.)

In the region being considered, shoals or sills usually exist between adjacent islands. The effect of abrupt changes in bottom configuration is to introduce vertical components of velocity into a passing stream. Such vertical displacement of stratified water may initiate a regular undulation of the density boundary. Similarly, the horizontal constriction of a stratified stream is likely to result in some vertical displacement of the density boundary which also may continue in a downstream direction.

One or more of these disturbing features may be responsible for instituting the wave patterns observed although the mechanism has not been determined.

Current velocities accompanying a tropic tide should be expected to produce large wave patterns over a greater proportion of a tidal cycle than would currents associated with an equatorial tide. This may account for the higher incidence of prominent wave patterns observed during the high tidal range of June 1 than during the lesser range of June 10.

Probable sources of internal waves--The largest wave patterns have appeared prominently in two regions, one between Galiano Island and the mainland, the other east of Gabriola Island. Present information does not permit exact definition of points or regions of origin but it appears likely that they are in the vicinity of channels such as Rosario Strait, Boundary Pass, Active Pass, and Porlier Pass which bound the southern part of Georgia Strait.

Acknowledgments--This survey was part of a study, in 1950, of the oceanographic phase of the Vancouver sewerage problem undertaken jointly by National Research Council of Canada, the Fisheries Research Board of Canada, the Pacific Oceanographic Group of the Canadian Joint Committee on Oceanography, and the Institute of Oceanography of the University of British Columbia, in the interests of the Vancouver and Districts Joint Sewerage and Drainage Board. The author, now with Defence Research Board of Canada at Victoria, was employed by the Fisheries Research Board while the investigation was being made. The photographs are British Columbia Government air photographs.

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STATISTICAL DESIGNS FOR SAMPLING BEACH SAND

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Abstract--The sampling of beach sand involves questions of sample size, depth of penetration, sample spacing, and sampling for seasonal variations. These problems can be studied by analysis of variance, in which experiments are designed to explore several relations at a time. The experimental design is controlled in part by natural subdivisions of the beach. These subdivisions include backshore, foreshore, and a nearshore submerged zone. Each displays certain "population" characteristics in terms of bedding, particle-size distribution, firmness, and other attributes.

Sampling experiments conducted over the past several years are described and summarized in terms of observed variations which occur on Lake Michigan beaches. In general, it was found that most beach characteristics are normally distributed within limited areas of the beach, and that the beach crest (berm) is an important dividing line between different populations of many beach attributes. A tentative design for sampling beach sand is submitted as a result of the studies.

Introduction--Sampling plans for any kind of deposit are controlled by the areal extent and characteristics of the deposit. The sampling of beaches appropriately includes the nearshore zone as well as the exposed beach. The zone of shore drift parallels the beach to moderate water depths, and the composition of the exposed beach is partly controlled by the nature of the drifting material. Above water the beach may be sampled with complete control of sample size, depth, and spacing. Underwater samples present other problems, and economic factors may enter in the added cost of securing numerous nearshore samples.

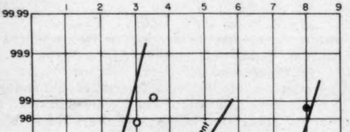

Fig. 1--Probability graphs of three beach properties, showing approximate agreement of closely spaced samples with normal curve

Characteristics of a deposit may be expressed in terms of the kinds of populations being sampled. The particle population comprising a beach is usually complex, and in a statistical sense it is not homogeneous when natural variations along and across beaches are considered. In any small area on a large beach, the particle size, shape, roundness, composition, porosity, water content, firmness, and other factors are relatively homogeneous within any layer, and closely spaced samples commonly show normal distributions of these properties as shown in Figure 1. These local areas satisfy the statistical conditions of homogeneous populations in that random samples from them have similar properties at some selected level of significance. As the size of the sampled area is enlarged, the variability among samples also increases, and the larger area may no longer be part of a single homogeneous population.

On this basis a beach may be considered as a series of homogeneous populations grading or merging into each other as the deposits are followed along or across the beach. Statistical limits for individual populations may be selected to test for significant geological or engineering differences. The individual population provides a variance due mainly to random sampling fluctuations, whereas statistically significant changes from one population to the next may be considered as due to variations in the natural "treatments" imposed by waves, currents, or other geological agencies.

It is well known that material transported along beaches is subjected to sorting and abrasional processes which produce systematic changes in particle size, shape, and other attributes. The objective of most studies is to measure these systematic changes and to relate them to the physical processes of the beach and the nearshore zone. The resulting data are of value in geological interpretation, engineering design, and other fields. Samples are commonly collected at intervals to bring out the systematic changes. In many cases only a single sample is collected at each point. This sample has a variability composed of the local variance plus the contribution made by the "regional" change in natural treatment of the material. In the general case, it is appropriate to make some provision for sorting out these two effects.

One of the more powerful statistical methods for sorting out variabilities is analysis of variance. In its simplest form the method compares variances within and between groups of data. If the ratio of the between-group variance to the within-group variance exceeds a selected critical value, the difference between the groups may be considered statistically significant. In terms of the present discussion, such differences may be interpreted as indicating that the populations represented by the several groups are different.

Closely associated with analysis of variance is the field of experimental design. Many sampling problems can be fitted into this framework by so collecting and analysing samples that the variances due to different causes can be sorted out and evaluated. The method provides an excellent device for studying problems of sample size, depth of sampling, sample spacing, and the like. Moreover, it is possible to design experiments to test for "regional" changes at any selected level of significance.

The present paper illustrates several analysis of variance models applied to beach sampling. The examples are drawn from experiments conducted by the writer and his students at Northwestern University during the past several years. The results are applicable to tideless Lake Michigan beaches, but certain generalizations of wider application can be inferred.

Bedding in beach deposits--Some beaches along Lake Michigan are composed of relatively homogeneous layers which show little variation within moderate depths of a foot or two, whereas others show heterogeneous arrangement of coarse and fine deposits from the surface downward. In a systematic study of beach structure, THOMPSON [1937] showed that beach bedding is a function of the part of the beach being studied. He divided beaches into an upper foreshore, extending "seaward from the crest of the beach to the zone of permanent saturation," and a lower foreshore, extending "seaward from the landward limit of the zone of saturation to low-tide shoreline." More recently McKEE [1953] included the backshore in his studies of beach structures. The backshore is defined as that part of the beach covered by water during exceptional storms only. The backshore may consist of one or more berms landward from the beach crest.

Both Thompson and McKee report that bedding in the upper foreshore is characterized by even, uniform layers that dip seaward at slight angles. Deposits on the lower foreshore appear to be very different from those of the upper foreshore, and are characterized by heterogeneity in surface expression (small basins, bars, and pools), in bedding thickness and attitude, and in composition (shells, micaceous detritus, etc.). According to McKee the backshore deposits display a third group of structures, also less regular than on the foreshore, consisting of landward dipping laminae cut at places by channels or troughs filled with steeply dipping beds, or with shells and detritus that settled as horizontal beds in the depressions. In barrier beaches the backshore deposits commonly merge into those of dunes or lagoons.

On many Lake Michigan beaches the backshore extends to the foot of a bank or sea cliff, without dunes or lagoon. As in the beaches described by Thompson and McKee, there is a marked difference between the backshore bedding and the bedding between the berm (beach crest) and the water line.

The marked differences between the several parts of beaches is an important feature in the design of beach sampling programs. Apparently the backshore, upper foreshore, lower foreshore, and shallowly submerged nearshore zones represent different beach populations because of differences in operative physical processes, that is in the natural treatments to which the zones are subjected. Waves wash up to the berm, but seldom cross it. Lakeward of the berm the sand is shifted about by wave action, but on the dry backshore, wind winnowing may selectively remove grains to the dunal belt. The sand becomes wetter and firmer lakeward of the berm; yet the crest of the berm may be the driest and softest part of the beach because of elevation and loose sand packing. As a result of these differing processes the beach displays its zonal arrangement and relative homogeneity or heterogeneity of attributes within each zone.

Figure 2 is a generalized map of sand penetrability on the beach at Wilmette, Illinois [KRUMBEIN, 1950]. The map shown was prepared in early spring, before the beach was disturbed by bathers. There is marked linearity of the pattern between berm and water line, and a more random pattern inland. The berm itself is consistently the softest part of the beach, except for scattered areas on the backshore and dunes. Similar patterns are shown in maps of average particle size, degree of sorting, particle sphericity, heavy mineral content, moisture content, and other properties.

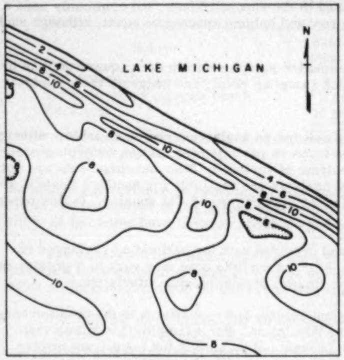

Fig. 2--Map of sand penetrability of beach at Wilmette, Illinois; length of beach segment about 500 ft; larger numbers mean greater penetrability

Bedding is evidently only one of several attributes which varies from place to place on the beach. The writer's studies were confined to the exposed parts of beaches, but INMAN [1952b] prepared pattern maps of particle size and mineral composition in California which included the nearshore zone. His maps show pattern linearity on the beach and in shallow water, with somewhat greater randomness in deeper water.

The systematic variations in pattern associated with beach zones suggests that sampling plans be designed to take account of these differences. Many beach samples have been collected with little regard for the portion of the beach being sampled, with the result that comparisons among beaches are hindered. BASCOM [1951] pointed out these shortcomings and suggested that the sample be collected at that point of the beach face subject to wave action at mid-tide level. Bascom's reference point falls within Thompson's upper foreshore zone, in which the bedding displays optimum uniformity.

Statistical evaluation of variability in beach deposits--Analysis of variance, as introduced above, was used in this study to evaluate the variability of beach deposits. A large number of analysis of variance models is available for application to sampling problems. Three basic models were used in the present study, but complete treatments of many models can be found in COCHRAN and COX [1950], GOULDEN [1952], SNEDECOR [1946], and other recent statistics texts. A review of five basic models adaptable to geological problems, and including the three to be used, is given by KRUMBEIN and MILLER [1953]. DIXON and MASSEY [1951] provide an excellent text which shows all the steps for computation in the more common models.

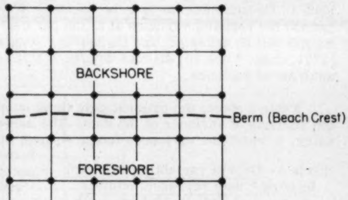

Fig. 3--Generalized beach sampling grid with rows parallel and columns normal to strand line

For unity of presentation, all experiments described here involve sampling grids designed for study of local populations, but extensions to regional studies are possible. A basic experimental design for studying local variations involves collecting one or more samples at each point on a grid. Figure 3 shows a grid with six columns and nine rows, yielding 54 "cells" for analysis of variance. The grid straddles the water line. The columns are oriented normal to the water line, and the rows lie parallel to the shore. Grid spacing is controlled in part by the size of the beach, although optimum spacing can be determined by designing for evaluation of spacing effects. The grids described here were confined to the exposed beach, and commonly used a spacing of 25 or 50 ft. It is not necessary that the row and column spacing be equal, although such spacing simplifies certain rate-of-change studies.

An alternative method is to randomize or systematize samples within each square defined by grid intersections. COCHRAN [1953] discusses such sampling plans, and suggests their superiority over sampling directly at grid intersections.

Each unit sampling area on the grid provides a cell for an analysis of variance table. Although the samples may be analyzed for several attributes (such as particle size, shape, and composition), each attribute becomes the basis for a separate analysis of variance. Size and shape data are not both entered in the same table, although methods of analysis are available for handling several attributes simultaneously (multivariate analysis and some applications of Chi square). In this paper only the single type of analysis is considered.

The study of several attributes of the beach sand provided data for estimating variances of different kinds of beach populations. For example, average particle size may vary to a greater or lesser degree than average particle shape; each has its own population characteristics.

Sample grids provide a mechanism for sorting out column and row effects in the data for comparison with the "residual" variance inherent in the population. For example, it is known that mean particle size changes along beaches. This is brought out by testing for significant differences between the columns. Particle size also varies across the beach, and this is detected by testing for significant row differences. If the sample grid is small enough, all samples taken from it will show only the residual variance characteristic of a single population. In that case there are no significant column or row effects. In a sense, therefore, the detection of significant row or column effects may demonstrate that a component of the "regional" or zonal change is included in the grid, that is, that the grid is large enough to include more than a single population.

Experimentation will be required to determine the optimum size of local beach grids for various types of beaches. Such grids can be located at suitable intervals along a beach, and the changing characteristics of the beach from grid to grid can be evaluated. This expenditure of effort is probably justified only in very detailed studies, or in trial runs designed to characterize various kinds of beaches. From the resulting data it should be possible to design much simplified sampling procedures applicable to a variety of beach conditions.

Bedding variability--An exploratory experiment on bedding variability in the backshore zone at Wilmette, Illinois, was conducted by digging 12 holes on a 30-ft grid spacing, and observing the nature of the bedding to a depth of 18 inches. The design was set up as follows: The number of beds in 18-inch samples is to be counted. If the between-row or between-column variance do not exceed the residual variance at a five per cent significance level, the hypothesis of homogeneous means will be accepted, and the bedding population will be considered uniform. DIXON and MASSEY [1951, chap. 7 and 10] discuss details of statistical inference and significance levels as applied to analysis of variance.

Table 1 shows the original data (total number of sand beds exposed in each hole), and Table 2, the analysis of variance of the data. The model used here is a two-factor basic form with single entry, in which the variances (mean square) between the columns (distance along the beach), and between the rows (distance across the beach), are compared with a residual variance which represents the "within variability." Table 2 is a standard form, described in DIXON and MASSEY [1951, p. 127], who also show the steps in computation. In essence the table indicates that the between-column and between-row variances are less than the "inherent" variability within the population, so that no significant differences in mean number of beds occur within the area sampled. Hence, for the significance level selected, the hypothesis of homogeneous means may be accepted.

Table 1--Grid of variability of beach bedding[a]; data represent number of observed beds in 18-inch depth from surface

(Along beach)

8	9	9	6
8	8	7	8
12	8	7	8

[a]Experimental data by D. A. Probst.

As a result of this analysis, one may say that the best estimate of the average number of beds in this part of the beach (to a depth of 18 inches) is the arithmetic mean of the 12 samples, or 8.2 beds. Moreover, an estimate of

Table 2--Analysis of variance of data of Table 1

Source	Sum of squares	Degrees of freedom	Mean square	F[a]
Between-columns (along beach)	7.00	3	2.33	< 1 NS
Between-rows (across beach)	2.20	2	1.10	< 1 NS
Residual	14.50	6	2.42	. . . . .
Total	23.70	11	. . .	. . . . .

[a] NS = not significant.

the population variance is provided by the residual variance, 2.42. The estimated standard deviation of the population is the square root of this value, or 1.56. That is, for such a population, two-thirds of the holes have between about six and ten beds.

The population estimates may be used to characterize this part of the beach backshore. If the beach were extensive, similar studies at, say, half-mile intervals would give successive population estimates that could be used in evaluating the "regional" changes along the beach.

The bedding experiment may be designed in various ways. If the beds exposed are counted on two opposite walls of each hole, a two-factor basic form with multiple cell entries is used for analysis of variance [DIXON and MASSEY, 1951, p. 134]. This form has certain advantages over the simpler form in that it provides a means for evaluating interaction effects between the rows and columns. When such interactions are present, a more critical value for estimating significant differences is provided by the multiple entry form. In bedding experiments such interactions may commonly be present, but the example in Tables 1 and 2 was selected to introduce an exploratory technique for first evaluation of main effects.

Variation in mean particle size--A large number of grids was used to study average particle size on beaches. These tests were conducted with the median, the geometric mean, and the phi mean [KRUMBEIN and PETTIJOHN, 1938, chap. 9]. The last is chosen for illustration here because it represents the center of gravity of the log size distribution, and is an unbiased sample statistic. As with the bedding-variability experiment, the statistical hypothesis is set up that the means are homogeneous at the five per cent significance level. If the critical value is not exceeded, the size population will be considered homogeneous.

Table 3 shows the data from a sampling experiment on the beach at Wilmette, Illinois. The example was chosen because the grid straddles the berm line from the backshore to the foreshore slope. The phi mean of each sample is entered in its proper cell position. The columns represent positions along the beach, and the rows represent positions across the beach. The upper three rows

Table 3--Grid of variation in log mean particle size; data expressed as phi means of particle size distribution

2.15	2.06	2.10	1.88	1.83
2.10	2.06	1.86	1.95	2.06
1.96	1.90	2.07	1.87	2.00
0.27	0.52	0.97	1.18	1.21

Table 4--Analysis of variance of data of Table 3

Source	Sum of squares	Degrees of freedom	Mean square	F
Between-columns (along beach)	0.0766	4	0.0192	< 1 NS
Between-rows (across beach)	5.0528	3	1.6843	26.48 **
Residual	0.7634	12	0.0636	. . . . .
Total	5.8928	19	. . . . .	. . . . .

are on the backshore, and the lower row is on the foreshore. The grid spacing was 50 ft between columns, and 25 ft between rows.

The analysis of variance of these data is shown in Table 4. The presence of significant row effects (compare the third and fourth rows) indicates that the grid extends into more than one population zone, whereas the absence of significant column effects shows that the populations on both sides of the berm are homogeneous over the length of the grid.

As with the bedding experiment, the design is improved if two or more closely spaced samples are collected at each grid point. A number of experiments which include replication showed that interactions are present in some instances, but data available at present do not indicate whether they are characteristic of all parts of beaches, or only of certain zones.

The analysis of variance data suggest that two particle-size populations are present in the sampled area, and that a biased estimate would arise if an average of all the samples were taken as a single population estimate. It seems preferable in this instance to average the 15 values in the upper three rows as an estimate of the backshore population mean, and to average the five values in the bottom row as an estimate of the upper foreshore population mean. In this case, moreover, the residual variance (mean square) is probably not a good estimate of population variance. This difficulty can be eliminated by running a separate analysis of variance on the upper three rows, as shown in Tables 5 and 6. The absence of significant column or row differences indicates a homogeneous population, with an estimated population mean, $M_\phi = 1.99$, corresponding to a geometric mean diameter of 0.25 mm. The residual variance, used as a population estimate, is 0.012; the estimated population standard deviation (for means) is the square root of this, 0.347. (A distinction should be drawn between the variance of the population means and the variance of the individual samples, as measured by the log standard deviation of the particle size distribution. This point is not pursued further in this paper.)

Table 5--Variation in log mean particle size, portion of grid used in Table 3

2.15	2.06	2.10	1.88	1.83
2.10	2.06	1.86	1.95	2.06
1.96	1.90	2.07	1.87	2.00

Table 6--Analysis of variance of the data of Table 5

Source	Sum of Squares	Degrees of freedom	Mean square	F
Between-columns (along beach)	0.0477	4	0.0119	<1 NS
Between-rows (across beach)	0.0068	2	0.0034	<1 NS
Residual	0.0961	8	0.0120	.....
Total	0.1506	14	.....	.....

The suggestion from this study is to design grids for individual population studies so that they do not straddle the berm. On the other hand, the beach may be considered as a "super-population" with a linear or exponential gradient. For such, a continuous grid with samples collected in the grid cells may be preferable.

Variations in other beach characteristics--Analyses similar to those for bedding and particle size were conducted for moisture content, sand penetrability, heavy mineral content, percentage of frosted grains, and other attributes. The grids extended across the berm or consisted of separate grids on each side of the berm, and they covered much of the backshore and foreshore areas. Significant differences were present in most characteristics across the beach, but not along the beach in the 200 or 300 ft covered by the grids. A table showing the level of variability for a number of beach characteristics is given in KRUMBEIN and MILLER [1953].

The problem of seasonal beach changes--Seasonal changes on beaches may be studied by analysis of variance. An appropriate model is a three-factor basic form, which permits evaluation of interaction effects. DIXON and MASSEY [1951] do not cover the details of this model, but a complete description may be found in GORE [1952, p. 49]. In using the model, samples are collected on the same grid at selected time intervals, and comparisons are made of the sets of samples in a single experimental design.

Several sampling grids on the beach at Wilmette, Illinois, provide data for exploratory analysis of this problem. The grids were not identical, but from their superposition it was possible to select a series of samples collected during 1948 and 1949 from nearly the same points on the beach. The matching samples lie landward of the berm on the beach backshore in four columns 100 ft apart and three rows 50 ft apart. The grid was thus 300 ft long and 100 ft wide. All samples were collected in half-pint ice cream cartons, which penetrate the beach about 1.6 inches.

The beach is subject to noticeable changes during the seasons, in that patches of gravel are strewn at times along the foreshore, and may occur occasionally on the backshore. A severe storm occurred just before April, 1949. This storm spread coarse sand and fine gravel over much of the beach, and this layer was still present in many places during the ensuing October sampling period.

The particle-size data may be organized in several ways. The average particle sizes in October and April may be contrasted to see whether seasonal effects occur; or the samples may be treated to see whether there was a net change in average size with time between April, 1948, and October, 1949. The latter organization is followed here for illustration.

The data are shown in the upper part of Table 7, with four entries in each cell, representing the geometric mean diameter of the particle size distribution at the times shown. The statistical hypothesis to be tested is that all the means are homogeneous at the five per cent significance level, that is, that there are no significant column, row, or time effects. The time effect is to be interpreted as a net change in particle size characteristics of the beach area through the two-year period.

Table 7--Variation in mean particle size on Wilmette grid during 1948-1949; data expressed as geometric mean diameter of particle size distribution

(Columns along beach; rows across beach)

Apr. 1948	0.25	0.24	0.27	0.33
Oct. 1948	0.25	0.28	0.30	0.32
Apr. 1949	0.26	1.07	0.53	0.33
Oct. 1949	0.31	0.24	0.41	0.51
Apr. 1948	0.27	0.27	0.27	0.25
Oct. 1948	0.27	0.29	0.28	0.36
Apr. 1949	0.28	1.13	0.48	0.41
Oct. 1949	0.32	0.39	0.31	0.29
Apr. 1949	1.74	0.70	0.44	0.31
Oct. 1948	0.26	0.28	0.26	0.30
Apr. 1949	0.80	0.72	0.55	0.54
Oct. 1949	0.23	0.22	0.32	0.59

Table 8--Analysis of variance of data in Table 7

Source	Sum of squares	Degrees of freedom	Mean square	F
Between-columns	0.1078	3	0.0359	< 1 NS
Between-rows	0.2350	2	0.1175	1.67 NS
Between-times	0.6389	3	0.2130	3.03 NS or *
Interaction				
Columns × rows	0.4217	6	0.0703	1.54 NS
Columns × time	0.9585	9	0.1065	2.37 NS or *
Rows × time	0.5390	6	0.0898	2.00 NS
Columns × rows X time	0.8100	18	0.0450	......
Total	3.7109	47	.....	......

Table 8 shows the analysis of variance for the data of Table 7. As is typical of three-factor basic forms, three first-order and one second-order interactions may be evaluated. After the table is set up, each first-order interaction is tested against the second-order interaction. In the present case the (column × row) and (row × time) interactions are not significant, but the (column × time) interaction is very close to the five per cent significance level (2.34 against 2.46).

The problem raised by this experiment is the choice of proper "error" for testing the main effects. If the (column × time) interaction is considered non-significant, the interaction sums of squares may be combined and divided by their combined degrees of freedom to obtain a total residual variance of 0.0699. With this as an error term, it is found that the column and row effects are non-significant, and the time effect is significant at the five per cent level. If the (column × time) interaction is considered significant, the main time effect may be tested against it, with a non-significant result.

The main results of this experiment are that the beach area may be considered homogeneous as far as row and column effects are concerned, and at best there is a doubtful net time change. The experiment is probably not decisive because the sampling points were not identical, and some unevaluated sources of variation, such as the use of different analysts, may influence the error term. It is interesting to note that INMAN [1952b], in his study of beach and nearshore patterns during different seasons, also concluded that the essential nature of the patterns was not seriously disturbed by seasonal changes.

The question of selecting valid errors, as illustrated by this example, is more related to the physical nature of the experiment than to the statistical principles on which the experiment is based. Some natural phenomena show significant interactions by the nature of the data, and some interactions may be introduced by laboratory treatment. The topic of the selection of valid error is treated in several statistics texts, such as SNEDECOR [1946], FISHER [1949], COCHRAN and COX [1950], and GOULDEN [1952].

Effect of sample size and depth of penetration--An exploratory experiment was designed to investigate the effect of sample size on the phi mean of the log particle size distribution. A metal sampling device, consisting of concentric rings, was forced into the sand to a selected depth. The sand between the rings was placed in separate containers to obtain a small central sample and successively larger annular ring samples. The ring was then forced to successively greater depths, resulting in 12 subsamples which comprised a total cylinder of sand about 11 inches deep and 12 inches in diameter.

The subsamples were combined into aggregates and sieved by the same analyst in such order that they represented a single sample growing in diameter and depth as the analysis proceeded. (Combination of the samples introduces a dependency among the successively larger samples, so that the variances may no longer be independent here. However, independent tests of the individual samples show similar relations for sample area and depth as indicated in this experiment.) The experimental design thus provided a means for studying the diameter and depth factors in sample size. The statistical hypothesis tested was that there were no significant differences among the phi means of the subsamples due to changing sample size. If the experiment were to show variance ratios exceeding a five per cent significance level, the hypothesis was to be rejected.

Table 9--Sample-size study[a]; data expressed as phi mean of particle size distribution

Depth of penetration	Diameter of sample area, inches			
	1.3	3.3	6.0	12.0
in				
1.6	1.65	1.67	1.58	1.65
	1.60	1.68	1.60	1.63
4.8	1.70	1.70	1.70	1.74
	1.68	1.69	1.63	1.70
11.2	1.57	1.51	1.53	1.51
	1.52	1.50	1.51	1.48

[a]Experimental data by A. H. Dewees.

The original data and analysis of variance are shown in Tables 9 and 10. This is a two-factor basic model with multiple cell entries [DIXON and MASSEY, 1951, p. 134], and illustrates the third analysis of variance model used in these studies. Each subsample was sieved twice, and the phi means for each analysis were entered separately in the twelve cells. The samples varied from a small cylinder 1.3 inches in diameter and 1.6 inches deep, to a maximum cylinder 11.2 inches deep and 12 inches in diameter. The analysis of variance table shows that the interaction (sample area × depth) is not significant at the selected level. Hence, the interaction and residual sums of

Table 10--Analysis of variance for data of Table 9

Source	Sum of squares	Degrees of freedom	Mean square	F
Between-columns (sample area)	0.0041	3	0.0014	1.54 NS
Between-rows (sample depth)	0.1285	2	0.0643	71.44 **
Interaction (column × row)	0.0092	6	0.0015	2.50 NS
Subtotal	0.1418	11	.....	......
Residual	0.0072	12	0.0006	......
Total	0.1490	23	.....	......

Combined error: 0.0164/18 = 0.0009.

squares were added and divided by their combined degrees of freedom, to obtain a total error mean square of 0.009. When the main effects are tested against this total error, it is seen that the increasing diameter of the sample is non-significant, but the depth of sampling is highly significant.

The top layer of the beach was rather pebbly, and it was thought that a significant difference would arise in the surficial sample as its area was increased. The depth effect was anticipated, inasmuch as the beach displayed several coarse and fine beds in the first foot of depth. It is hazardous to generalize from a single experiment, but the results suggest that a sand sample of small diameter is as effective as a large one of the same depth for studying particle size properties on beaches. Whether other beach attributes, such as heavy mineral composition, also show similar homogeneity can be tested on the same sand samples. The experiment supports the common practice of taking samples only a few inches in diameter. The problem of optimum depth of sampling requires more study. If there is a general tendency in beach studies, it is to emphasize the surficial layers, although for certain studies deeper samples may be more appropriate.

The sample used in this experiment was collected on the backshore about ten feet landward of the berm. Additional experiments on the backshore and foreshore of additional beaches should yield data of value in settling the question of sample size for most sand beach studies. It is interesting as a sidelight that if the interaction proves to be generally non-significant, a single analysis of each sample is adequate for such studies.

Tentative proposals for beach sampling programs--The examples of designed experiments reported here represent several from about 50 experiments involving various beach attributes. In all instances it was found that the variance across the beach is much greater than that along the beach. This is in accord with common knowledge, and serves to emphasize the necessity for sampling equivalent parts of beaches in comparative studies, as BASCOM [1951] pointed out.

Although present data cover only exposed parts of beaches on tideless lakes, some suggestions applicable to ocean beaches can be derived from them. The fact that many beach properties vary in a similar manner implies that inspection of one or two conspicuous beach features can serve to guide the sampling design. Easily seen properties are gross particle size, beach firmness, and beach bedding. By walking over the beach, and digging an occasional hole about a foot deep, a good idea of the expected homogeneity or heterogeneity may be had.

The first problem is to locate division lines between the several beach zones. Presence of berms, knowledge of mean and low tide levels, and presence of dunes or other features behind the backshore permit organization of the sampling plan according to backshore, upper foreshore, lower foreshore, and submerged nearshore. The second problem is to select the spacing of lines normal to the beach (sampling traverses), along which the samples are to be collected. The length of the beach segment, and its over-all homogeneity or heterogeneity (such as a generally uniform sandy nature as against patchy gravel occurrences) will influence the spacing of the sampling traverses. It is difficult to generalize on this aspect, inasmuch as the purpose of the study enters the spacing problem. For studies of changes in particle size or other properties along the beach, the traverses are set far enough apart to bring out the "regional" as opposed to the "local" changes. A minimum of six or seven traverses seems to be indicated.

Each traverse provides a line normal to the shore, extending from the landward edge of the backshore to an appropriate nearshore depth, presumably at least 30 ft. The minimum sampling plan would include one sample from each beach zone, with the sample on the upper foreshore collected at Bascom's reference point. A more satisfactory plan involves collecting several samples from a circle around each stake. If the position of the samples is randomized by coin tossing, personal bias will be reduced. This plan is a form of stratified sampling.

The principle involved here is that it is more efficient to collect four small samples, and to analyze each one once, than to collect one large sample and analyze it several times. The several smaller random samples provide data for better estimates of the mean particle size of the population at the sampling site, and with four samples it is possible to make an unbiased estimate of the population variance of means. It is recognized that such multiple sampling may be economically unfeasible for underwater samples, in which case the lower reliability of the estimates may be offset by considerations of economy.

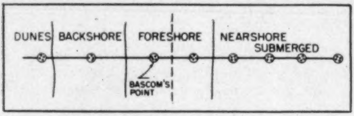

Fig. 4--Beach sampling traverse showing positions of sampling points with four randomized samples in each

Figure 4 shows a sample traverse extending from the dunes into the nearshore area. Four randomized samples are indicated in each zone on the exposed beach and at each underwater point. As mentioned, single underwater samples may be more feasible, unless an underwater sample could be devised which collects four closely spaced samples. For wide beaches it may be desirable to sample each beach zone at points additional to the mid-zone stake indicated.

Depth of sample penetration is determined by the nature of the study. Most beach samples are relatively shallow, and seldom extend for more than a few inches below the surface. It is conceivable, however, that some studies could involve samples a number of feet deep. The problem of most effective sample depth requires systematic examination. On the assumption that shallow samples are adequate for most purposes, it is suggested that relatively small samples be taken, in the form of cylinders two or three inches in diameter and depth.

As presently conceived, the tentative sampling plan involves collecting samples representative of each beach zone along each traverse, with the underwater samples spaced either according to fixed depths below datum, or with fixed distance from datum shoreline. As with sample size, the selection of proper underwater spacing requires further study.

The number of samples required for a program involving six traverses, with four samples from each exposed beach zone, and single underwater samples at say five nearshore locations, would be about 125. Such a spread of samples would bring out characteristics and changes along the beach zones on a level of reliability adequate for many studies. Moreover, it would provide comparative data for study of a group of beaches; and if the traverses are fixed in position, seasonal effects could be included in the master design.

The data from the sample traverses may be carried along the beach, zone by zone, or the samples along each traverse may be averaged to obtain a gross value characterizing the whole beach at the traverse. It seems preferable to analyze each sample separately, and to combine the data arithmetically, rather than to combine the samples before analysis. In this way the variability among samples is preserved for variance studies.

For very detailed studies, or for trial runs on establishment of principles, a beach grid as illustrated in Figure 1, extending from the backshore or dune belt to the outer limit of the submerged zone could be set up at each traverse. Instead of collecting samples at the grid stakes, they could be randomized or systematized within the cells, as illustrated by COCHRAN [1953, p. 184]. Systematization is more convenient for underwater samples.

The discussion thus far places major emphasis on the size distribution of samples from sand beaches. The same samples may be used for particle shape, heavy minerals, and other attributes. If penetrometer tests are to be included, the moisture content and bulk density (packing or porosity) ty) of the sand may also be important.

Gravel beaches present different problems, mainly in connection with sample size. Little has been done to the writer's knowledge on the relation of sample size to particle size for comparable reliability of analytical results, although as long ago as 1926 Wentworth [KRUMBEIN and PETTIJOHN, 1938, p. 31] suggested a doubling of the sample volume for each main size group, starting with 125 cc for clay, up to one liter for granule gravel. The problem could presumably be handled by a designed experiment.

Concluding remarks--The present paper introduces no radical innovations in beach sampling, but does attempt to show that slight modification of present sampling techniques can result in considerably more information for comparable expenditure of effort. Analysis of variance and design of experiments, as developed by statisticians and applied in a variety of sciences, have amply demonstrated their value in sampling problems. The several examples given illustrate some of the kinds of problems that can be attacked, and suggest many more that may prove helpful in developing and standardizing beach sampling procedures.

Analysis of variance is useful not only in testing for homogeneity of beach deposits, but it provides a foundation for efficient and unbiased estimates of various population parameters. The topic of components of variance, which extends the method in this direction, has not been touched upon, although full discussion of this subject can be found in many statistics texts. DIXON and MASSEY [1951, p. 142] provide an excellent introduction to the concepts. Similarly, some of the assumptions on which analysis of variance is based are not developed here, but an introductory treatment for geological applications is given by KRUMBEIN and MILLER [1953]. DIXON and MASSEY [1951] discuss the subject in Chapter 10.

No attempt was made to cite the voluminous literature on beaches in terms of sampling procedures. A number of special techniques, not intentionally omitted, deserve re-analysis in the light of experimental design. OTTO's [1938] concept of a sedimentation unit as a basis for sampling may be mentioned in this connection.

A number of other problems touched upon only by implication deserve fuller analysis in the light of modern statistical concepts. One is the selection of proper sample statistics to describe beach properties. The median and geometric mean diameters, Trask's sorting coefficient, and other statistical measures widely used may not be the most efficient or unbiased statistics, especially as estimators of population parameters. INMAN's [1952a] recent proposal for analysis of cumulative size curves is a step in the direction of such re-evaluation. Until data are available on the sampling distributions of the statistics themselves, and on the relation of these to population parameters, the subject may be considered open for further study.

The tentative sand sampling plan described here is offered as a progress report in the hope that it will stimulate development of more comprehensive programs. The writer is indebted to his colleagues at Northwestern University and to numerous graduate students who helped secure the basic data on Lake Michigan beaches. Meyer Dwass of the Mathematics Department at Northwestern was most helpful in discussion of statistical problems and selection of experimental designs. R. O. Eaton of the Beach Erosion Board extended every facility, and suggested the need for organized study of the problem.

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THE ISOPARAMETRIC METHOD OF MAPPING ONE ELLIPSOID ON ANOTHER

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Abstract--Geodetic positions can be transferred from one ellipsoid to another by calculating x, y coordinates on some standard projection for the first ellipsoid, and then, regarding the x, y coordinates as identical on the two ellipsoids, reversing the computation using the constants and tables appropriate to the second ellipsoid. It is shown that the distortions introduced in this way are proportional to the distortions of the projection used for calculating the x, y coordinates, and that the ratio of proportionality is equal to the fractional change in the Gaussian curvatures.

In transferring geodetic positions from one ellipsoid to another, many mathematicians in the Corps of Engineers, U. S. Army, make use of a quite simple and direct procedure. In the course of discussions with European geodesists, this procedure has been questioned, and the lack of an adequate theoretical explanation for it has been pointed out. This paper is an attempt to supply the required explanation.

Let us suppose that we are given a set of latitudes, ϕ, and longitudes, λ, in the area G. These have been calculated from the original measurements of angles and distances by means of tables for the spheroid A, starting from the datum point, whose latitude and longitude, ϕ_1, λ_1, result from astronomic measurements at one or more stations. It is desired to convert all the latitudes and longitudes to those latitudes and longitudes which would have been obtained if the spheroid B had been chosen instead. The first step is to calculate coordinates which we may designate as u^1 (northing) and u^2 (easting), based on some standard projection, such as the transverse Mercator, and referred to spheroid A by the use of the appropriate tables. The superscripts on u^1, u^2 merely distinguish the coordinates; to indicate the squares, we shall write $(u^1)^2$, $(du^1)^2$ and the like. The origin is taken at the point ϕ_0, λ_0 which should usually be near ϕ_1, λ_1, since this is the point whose latitude and longitude will be unchanged. The projection is chosen with an eye to obtaining a cartographically satisfactory representation of the area; that is, the axis of strength, along which the derivatives of the scale factor are zero, is made to coincide with the long axis of G, so far as convenient.

Next, the values of u^1, u^2 are converted back to latitude and longitude, using, this time, tables for the same projection, but referred to the new spheroid, B, with the origin still at ϕ_0, λ_0. This procedure may be called the isoparametric procedure since the parameters u^1, u^2 are the same on both spheroids.

Evidently the procedure is not utterly unreasonable. When the points from spheroid A are converted to rectangular coordinates u^1, u^2, it is almost as though they had been expressed in terms of the original measurements in distance and angle on the ground. Near the origin, in particular, and especially for short lines, the ground measurements can be obtained from the coordinates immediately, with a very fair degree of accuracy, without any special assumption about the spheroid. It is, in fact, an operational procedure in many places, for example, Sweden and Madagascar, to pass directly from ground measurements to rectangular coordinates, even in first-order triangulation, by means of formulas so constructed that the role of the assumed spheroid is a very small one, indeed. In this sense, one can almost say that the rectangular coordinates do not presuppose any spheroid. We put in the elements of the spheroid when we pass through tables based on B to latitudes and longitudes.

The crucial step in the isoparametric method is the one in which, from regarding the rectangular coordinates as being coordinates on A, we change to regarding the identical numbers as coordinates on B. If this step is justified, then all the rest is pure routine. There is no doubt, for example, about the possibility of transforming latitudes and longitudes on A into rectangular coordinates on a grid whose mathematics are adequately known. The resulting coordinates will be free from ambiguity, and will represent exactly the same positional relationship among the points. Nor is there any difficulty about transforming rectangular coordinates on spheroid B into latitudes and longitudes on B. The problem comes at the step when we decide that we shall consider the rectangular coordinates which we have worked out on A as belonging on B also.

There will be some distortions of the original data at this step. For example, on the transverse Mercator projection the scale, m, that is, the ratio of distance on the projection to ground distance, is given approximately by

$$m = 1 + \frac{(u^2)^2}{2\rho\nu} \quad \text{.......................} \quad (1)$$

where u^2 is the easting reckoned from the central meridian, and ρ, ν are respectively the radii of curvature in the meridian and perpendicular to the meridian. If we change to a new spheroid, keeping u^1 and u^2 identical numbers, then evidently we will change m, because the product $\rho\nu$ has changed. Obviously, also, the change will be small. Good cartographic practice requires that m - 1, the map distortion, be kept, if possible, below paper shrinkage, that is, less than 0.1 pct. The change in $\rho\nu$ in passing from one spheroid to another is not likely to exceed 1:5000; hence the change of m is not likely to be more than 1:5,000,000. Such a scale-change has no significance whatever for field measurements; the best of these do not appear to be much better than 1:1,000,000. On the other hand, it can, of course, lead to misunderstandings in the computing room. It is therefore worth while to see exactly how this method compares with other methods for transforming coordinates.

Since we seek above all to eliminate misunderstandings and to carry conviction, it appears best to make use of mathematical language. Fortunately, the problem has been treated by the mathematicians in some detail. The eighth chapter of LEVI-CIVITA [1926] discusses the relation between two different metrics assigned to the same analytical manifold; and this is mathematical language for our problem. The two different metrics can be conveniently thought of as two different surfaces, in our case the spheroids A and B, and the analytical manifold as the set of values of u^1, u^2 which are the same for the two spheroids. The footnotes at the beginning of his chapter make it clear that it is this sort of situation that Levi-Civita had in mind.

Levi-Civita proceeds to set up the fundamental quadratic forms in the two metrics (spheroids), which, if we employ the summation convention, and if we write the indices on the coordinates as superscripts, become

$$ds^2 = a_{ij}\, du^i\, du^j \quad \text{.......................} \quad (2)$$

$$(ds')^2 = a'_{ij}\, du^i\, du^j \quad \text{....................} \quad (3)$$

where ds is an infinitesimal ground distance on the first spheroid; ds' the corresponding quantity on the second spheroid; i and j range from 1 to 2. For any conformal projection, (2) becomes

$$ds^2 = \frac{1}{m^2}\left[(du^1)^2 + (du^2)^2\right] \quad \text{.................} \quad (4)$$

the familiar relation for the scale factor, with m as the scale. For non-conformal projections the formulas are more complicated. If the rectangular coordinates are orthogonal on the ground, the scale factor for the u^1 direction is no longer the same at a given point as the scale factor in the u^2 direction; and if the coordinates are not orthogonal it will be necessary in addition to make use of a product term in du^1, du^2. For example, on the azimuthal equidistant projection, we have up to terms of the second order in the a_{ij} by substitution from the table, page 392, of CHOVITZ [1952] into the Eq. (3), page 380, and thence into (1), page 380, bearing in mind Eq. (30), page 389

$$ds^2 = \left[1 - \frac{1}{3}K\,(u^2)^2\right](du^1)^2 + \frac{2}{3}K\,u^1\,u^2\,du^1\,du^2 + \left[1 - \frac{1}{3}K\,(u^1)^2\right](du^2)^2 \quad \text{..} \quad (5)$$

where K is the Gaussian curvature, $1/\rho\nu$. These coordinates are identical with those sometimes called Riemann canonical coordinates [BLASCHKE, 1945].

The relation of the ds' to ds is clearly governed by the relation of the two fundamental tensors a_{ij} and a'_{ij}.

These tensors will also tell us, in the case of a non-conformal projection, the amount of angular distortion which has been introduced. If we consider the infinitesimal vectors du^i, δu^j, one along each side of an angle θ, then we can define the so-called parameters of the direction (not the same as the parameters u^1, u^2 which are unchanged by the transformation) as follows

$$\lambda^i = \frac{du^i}{ds}; \quad \mu^j = \frac{\delta u^j}{\delta s} \quad \dots\dots\dots\dots (6)$$

where

$$\cos\theta = a_{ij}\,\lambda^i \mu^j \quad \dots\dots\dots\dots (7)$$

[LEVI-CIVITA, 1926, p. 93, Eq. (8)]. The change of θ in passing from one ellipsoid to another arises in part from the change of a_{ij}, and in part from the change of λ^i, μ^j arising from the changes in ds and δs.

It is particularly interesting to examine the results of these procedures for the Helmert method of representing one ellipsoid upon another. It will be shown below that the Helmert method is equivalent to mapping by way of the azimuthal equidistant projection. For the moment, let us take this result for granted. Let us consider a point at a distance of 200 km from the initial point, and let us ignore the variations of **K** with position on the given ellipsoid. Suppose that the origin of the system is at 45° of latitude and that the coordinates of the point are $u^1 = 160$ km, $u^2 = 120$ km, and that $du^1 = -1$ meter and that $du^2 = +1$ meter. The computation of ds on the two spheroids is shown in Table 1. It is based on (5).

Table 1--Computation of ds, at latitude 45°N

Quantity	Bessel	International
ρ	6,366,676 meters	6,367,587 meters
ν	6,388,065 meters	6,389,135 meters
$K = 1/\rho\nu$	2.45877×10^{-14} (meters)$^{-2}$	2.45801×10^{-14} (meters)$^{-2}$
$(u^2)^2/3$	. . . .	$+ 4.800\,000 \times 10^9$ (meters)^2; $(du^1)^2 = +1$
$2(u^1u^2)/3$	. . . .	$+ 12.800\,000 \times 10^9$ (meters)^2; $(du^1u^2) = -1$
$(u^1)^2/3$	. . . .	$+ 8.533\,333 \times 10^9$ (meters)^2; $(du^2)^2 = +1$
a_{ij}	$1 - 4.800\,000 \times 10^9$ **K** $+ 6.400\,000 \times 10^9$ **K**	$+ 6.400\,000 \times 10^9$ **K** $1 - 8.533\,333 \times 10^9$ **K**
ds^2	$2 - 26.133\,333 \times 10^9$ **K**	
ds^2	1.999 357 441	1.999 357 640
ds	1.413 986 365	1.413 986 436

$$\frac{\text{International length}}{\text{Bessel length}} = 1 + 50 \times 10^{-9}$$

We next calculate the angle θ between this line, which we may call du^i and another line, δu^j, whose components are $\delta u^1 = +1$ and $\delta u^2 = 0$. The length of the line δu^j is given, by similar computations, as Bessel spheroid, 0.999 940 988 meters; International ellipsoid, 0.999 941 006 meters. The parameters of the direction, for the line du^i, may be denoted as λ^i; those for the line δu^j as μ^j. Substituting the actual numbers in (6) on the Bessel spheroid, $\cos\theta = -0.707\,067\,368$; on the International ellipsoid, $\cos\theta = -0.707\,067\,380$. Whence θ, International minus Bessel equals $-0\overset{''}{.}0036$.

In these calculations, the effect of terms above the second order in the a_{ij} has been neglected. In consequence, the calculations of ds and cos θ are not exact. On the other hand, the neglected terms are small, and the variations produced in them by the change of spheroid are smaller yet, by a factor of about 5000; hence the ratio of the two values of ds, and the difference of the values of θ are accurate.

By these methods, it is possible to evaluate the errors which will be produced if the isoparametric method is applied, making use of any of the projections listed by Chovitz.

In order to have a more general view of the problem, we calculate the expression for the square of a length element in locally Cartesian coordinates. Since these are identical with true Cartesian coordinates up to terms of the second order in the a_{ij}, we have, by a Taylor expansion

$$a_{ij} = \delta_{ij} + \frac{1}{2}\frac{\partial^2 a_{ij}}{\partial u^k\,\partial u^h}\,u^k\,u^h + \cdots \tag{8}$$

$$ds^2 = \left(\delta_{ij} + \frac{1}{2}\frac{\partial^2 a_{ij}}{\partial u^k\,\partial u^h}\,u^k\,u^h\right) du^i\,du^j \tag{9}$$

For ordinary Cartesian coordinates, we would have

$$d\sigma^2 = \delta_{ij}\,du^i\,du^j \tag{10}$$

As a measure of the errors of the representation, it is convenient to take the quantity $ds^2 - d\sigma^2$ which we shall call ϵ. The actual "error in length" is $ds - d\sigma$. The relation between the two quantities is clearly given by

$$ds - d\sigma = \frac{ds^2 - d\sigma^2}{ds + d\sigma} \doteq \frac{\epsilon}{2\,d\sigma} \tag{11}$$

Subtracting (10) from (9)

$$\epsilon = \frac{1}{2}\frac{\partial^2 a_{ij}}{\partial u^k\,\partial u^h}\,u^k\,u^h\,du^i\,du^j \tag{12}$$

CHOVITZ [1952, Eq. 21], points out that in locally Cartesian coordinates we know that

$$2K = 2\frac{\partial^2 a_{12}}{\partial u^1\,\partial u^2} - \frac{\partial^2 a_{11}}{\partial u^2\,\partial u^2} - \frac{\partial^2 a_{22}}{\partial u^1\,\partial u^1} \tag{13}$$

This result can be immediately obtained from the formula of GAUSS [1827, p. 236] by reducing to locally Cartesian coordinates.

Since the errors of length are proportional to the second derivatives of the a_{ij}, it is evident that most cartographic projections will be so chosen as to make these second derivatives as small as can conveniently be done. It is also evident from (13) that not all the second derivatives can be made equal to zero; at least some of them must be of the order of magnitude of K. This is the underlying reason why the coefficients of K in Chovitz's table of projections are all of the order of unity.

Returning now to the original problem of mapping one ellipsoid on another, we can construct an equation similar to (12) for the new ellipsoid (quantities peculiar to the new ellipsoid being primed)

$$\epsilon' = \frac{1}{2}\frac{\partial^2 a'_{ij}}{\partial u^k\,\partial u^h}\,u^k\,u^h\,du^i\,du^j \tag{14}$$

The u^k and u^h, and the du^i, du^j are not primed because they are by hypothesis the same on both spheroids. The second derivatives of the a'_{ij} must satisfy an equation like (13), namely

$$2K' = 2\frac{\partial^2 a'_{12}}{\partial u^1\,\partial u^2} - \frac{\partial^2 a'_{11}}{\partial u^2\,\partial u^2} - \frac{\partial^2 a'_{22}}{\partial u^1\,\partial u^1} \tag{15}$$

Evidently the change in the square of the length of a very short line in passing from one ellipsoid to another by the isoparametric procedure is given by subtracting (12) from (14)

$$\epsilon' - \epsilon = \frac{1}{2}\left(\frac{\partial^2 a'_{ij}}{\partial u^k\,\partial u^h} - \frac{\partial^2 a_{ij}}{\partial u^k\,\partial u^h}\right)u^k\,u^h\,du^i\,du^j \tag{16}$$

In this equation, the differences of the second derivatives are subject to an equation analogous to (13), formed by subtracting (13) from (15), namely

$$2(K'-K) = 2\,\frac{\partial^2}{\partial u^1\,\partial u^2}(a'_{12}-a_{12}) - \frac{\partial^2}{\partial u^2\,\partial u^2}(a'_{11}-a_{11}) - \frac{\partial^2}{\partial u^1\,\partial u^1}(a'_{22}-a_{22}) \ldots (17)$$

It is evident from (17) that unless the Gaussian curvatures of the two ellipsoids are equal, not all the differences of the second derivatives of the a_{ij} can be equal to zero. The analogy with the representation of the ellipsoid on the plane can be pushed even farther, for we see that at least some of the differences of the second derivatives must be of the order of magnitude of the difference of the Gaussian curvatures.

Now if a_{ij} and a'_{ij} correspond to any ordinary projection, we shall find that the second derivatives are proportional to the Gaussian curvatures. This result is implied by CHOVITZ [1952, pp. 389 and 392], when he factors out the Gaussian curvature from all of his a^{ij}_{hk}, and finds purely numerical quotients. The result is purely empirical; it would not hold for the latitude and longitude system near the equator. In view of equations like (13), however, it is not reasonable to construct coordinate systems which lack this property. For the listed map projections, (16) can be written by the usual principles of proportion

$$\epsilon' - \epsilon = \frac{K'-K}{K} \cdot \frac{1}{2} \cdot \frac{\partial^2 a_{ij}}{\partial u^k\,\partial u^h}\, u^k u^h\, du^i\, du^j \ldots\ldots\ldots\ldots (18)$$

or, substituting (12)

$$\epsilon' - \epsilon = \frac{K'-K}{K}\,\epsilon \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

and making use of (11)

$$ds' - ds = \frac{K'-K}{K}\,(ds - d\sigma) \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

Equation (20) asserts: If one ellipsoid is mapped upon the other by the isoparametric method, using the projection p as intermediary, then up to terms of the 2nd order in the coordinates (the origin being on the axis of strength) the length distortions introduced on the second ellipsoid bear to the length distortions introduced between the first ellipsoid and p the same ratio as the difference of the Gaussian curvatures bears to the Gaussian curvature of the first ellipsoid.

It follows that we may gain insight into the length distortions which will be produced in mapping one ellipsoid on another by this process if we consider the well-known cartographic distortions which accompany the transfer from the ellipsoid to the plane. The distortions from one ellipsoid to another will be less than the cartographic distortions, in a ratio which is usually of the order of 1:10,000; but they will be similar in kind and similarly distributed.

In the case of an area which has been mapped on a single projection, it may not be necessary to alter the grid coordinates in any way in order to convert from one ellipsoid to another. We may simply declare that the given coordinates are to be regarded as being on a new ellipsoid. (This may not be done, however, with the system of latitudes and longitudes because they are not locally Cartesian except at the equator and because for this system the a_{ij} involve the quantities ρ and ν, as well as K.) If the projection was devised by a competent cartographer, it is evident that the cartographic distortions will have been minimized throughout the area; it is thus automatically the most advantageous type of projection to use in transferring data from one ellipsoid to another. In a sense, one can say that the grid coordinates are independent of the assumed spheroid, at least up to terms of the third order in the coordinates.

In other cases, it may be inexpedient to make use of the projection given for the original grid coordinates. At such times, the coordinates of the original grid may be converted to a new grid by means of formulas for passing from one grid to another. In these formulas the Gaussian curvature is involved. The question arises, therefore, whether to substitute the Gaussian curvature of the first spheroid or that of the second spheroid. If we substitute the Gaussian curvature of the second spheroid, then this implies that we regard the grid coordinates of the first projection as being on the second spheroid as well as the first; hence the transformation from spheroid to spheroid takes place with the characteristics of the first projection. Conversely, if the Gaussian curvature of the first spheroid is used in the grid-to-grid transformation, then the second grid is assumed to be on both spheroids, and hence the spheroid-to-spheroid transformation takes place with the characteristics of the second projection.

It is possible, by the use of (20), to make a rapid numerical estimate of the length distortions introduced by mapping from one ellipsoid to another. We need only apply (32) of Chovitz's paper, calculating the a_{ij} by means of Chovitz's table, but replacing K by K' - K.

Let us now consider the Helmert technique of mapping from one ellipsoid to another. It has been pointed out by BODEMÜLLER [1944] that this projection resembles the Hatt projection, often called the azimuthal equidistant projection of the ellipsoid on the plane. That is to say, by the Helmert technique the polar coordinates of a point, that is, its geodetic distance and azimuth from a central point, are unaltered. It follows that the rectangular coordinates on the Hatt projection, which amount simply to the resolution of the polar coordinates into Cartesian coordinates, are likewise unaltered.

We see, then, that the mapping of one ellipsoid upon another, by the Helmert method, bears the same relation to the isoparametric technique as the Hatt projection bears to the general body of useful map projections, at least so far as the deformations in length are concerned.

In the above-mentioned paper BODEMÜLLER [1944] describes four other projections of one ellipsoid upon another. The first of these which he denotes by U_I is a conformal projection of one ellipsoid upon another, in which all azimuths of infinitesimal lines are preserved. Evidently we shall be able to obtain this property if we map the first ellipsoid onto a plane, by the Mercator projection, in which the position-angle of an infinitesimal line is equal to its azimuth on the Earth's surface; and then transfer from the plane to the second ellipsoid by the inverse formulas for the Mercator projection. Since the Mercator projection is locally Cartesian only near the equator, it is evident that this method will distort areas at high latitudes by an amount considerably greater than necessary, as Bodemüller points out.

The second of Bodemüller's projections, U_M, is conformal and the distortions of length are zero along the central meridian; furthermore, the rate of change of length distortion is zero along the central meridian. It is thus a representation analogous to the transverse Mercator or Gauss projection.

I shall show that U_M must be identical with the mapping produced by the isoparametric method, using the transverse Mercator projection as the intermediary. To show this, let us denote the latitude and longitude on the original spheroid as ϕ, λ. From these, we calculate, by the aid of the usual tables for the transverse Mercator, appropriate to the first spheroid, the plane coordinates u^1, u^2 (which are, of course, the ordinary x and y, or N and E). In the same manner, on second spheroid, let us denote the latitudes and longitudes as Φ, Λ, and let us consider these as formed from ϕ, λ by the transformation U_M. Let us form rectangular coordinates v^1, v^2 from Φ, Λ, as before, by the use of standard tables for the transverse Mercator, appropriate to the second spheroid. Let us further specify that $u^1 = v^1$, $u^2 = v^2$ for at least one point of the central meridian, as can be done by the addition of a constant to v^2, if necessary.

Now the mapping of u^1, u^2 onto v^1, v^2 is a conformal mapping, since (a) the mapping of u^1, u^2 onto the first ellipsoid is conformal; (b) the mapping of the first ellipsoid on the second ellipsoid is conformal; and (c) the mapping of the second ellipsoid onto the plane of v_1, v_2, is conformal. It follows that $v^1 + iv^2 = f(u^1 + iu^2)$ where f is an analytic function. Furthermore, we have that

$$u^1 = v^1$$

$$u^2 = v^2$$

not only at a single point of the central meridian, by hypothesis, but at all points of the central meridian, because, (a) the central meridian remains a geodetic line in all of the mapping involved; (b) the central meridian coincides with the axis of the ordinates on both projections by the definition of the transverse Mercator; and (c) the scale is unaltered along the central meridian, by the definition of the transverse Mercator mapping of the ellipsoid on the plane, and the analogous definition of the mapping of one ellipsoid on another by the transverse Mercator. Hence we have

$$u^1 \equiv v^1 \quad \text{and} \quad u^2 \equiv v^2$$

for all points within the area in which the mapping is free of singularities, by a well-known theorem in the theory of the complex variable [OSGOOD, 1928]. It follows that the isoparametric method of mapping by way of the transverse Mercator projection is identical with Bodemüller's U_M.

This may also be established by inspection of Bodemüller's (101′), if we note that the bracket in Bodemüller's formula is approximately the logarithmic differential of the Gaussian curvature, that is

$$\frac{\delta K}{K} = \left[\frac{\delta a}{a} - \cos^2 \phi \, (1 - t_0^2) \, \delta \alpha\right] \ldots\ldots\ldots\ldots\ldots \quad (21)$$

where, following Bodemüller's notation, a is the Earth's semi-major axis, α the flattening, t_0 the latitude at the origin of the projection. The equivalence is somewhat approximate, since it requires setting

$$(u^2)^2 = \frac{\cos^2 \phi \, \Delta \lambda^2}{K^2} \ldots\ldots\ldots\ldots\ldots\ldots \quad (22)$$

that is, neglecting terms of the order of the square of the eccentricity or the fourth power in $\Delta\lambda$.

In the same way, the identity of Bodemüller's (105′) and (107′) with the results of the isoparametric technique on the Lambert and the stereographic projection respectively may be established.

It is evident that the deformations produced by the isoparametric method are of the same order as those produced by other methods; and that the method gives an insight into the deformations which may be useful to the planner as well as to the computer. It is hoped that the method may be of service to others.

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CAN THE RATE OF WASH LOAD BE PREDICTED FROM THE BED-LOAD FUNCTION?

H. A. Einstein and Ning Chien

Abstract--There exist two types of sediment load, one that bears a certain relationship with the discharge (bed-material load), and the other which does not (wash load). The result of flume study indicates that the transport rate of wash load, just as that of the bed-material load, can be calculated according to the Einstein bed-load function if the instantaneous bed composition is known. On the other hand, the bed-material load is equally available in the entire bed, but only the surface bed layer contains any significant amount of wash-load material. Any change of flow or of sediment supply may immediately change the composition of the wash-load material in the bed. The bed composition as determined from the instantaneous condition of the channel has no lasting significance so far as the wash load is concerned, and this makes the prediction of the wash-load rate from the bed-load function impossible.

Introduction--In studying sediment-transportation problems, it has long been recognized that for certain sediment sizes there appears to exist no relationship between their rates of motion and the flow. Thus, VETTER [1937] stated

> The fine material, not available in the bed of the stream for many miles upstream from the point of observation, must originate elsewhere on the river or on its tributaries and it cannot be expected that any fixed relationship should exist between the discharge and the load of the finer material. . . If the part of the silt load which lies within the range of sizes abundantly available in the bed bears a fixed relationship to the discharge, there is no reason to believe that this relationship will be materially changed if the finer part of the load is partly or entirely eliminated.

This statement is believed to have been the first one which pointed out clearly that there exist two types of sediment load, one that bears a certain relationship with the discharge and the other which does not. GRIFFITH [1944] named the former one the bed sand and the latter one the alluvial silt. He suggested that the bed sand is supported by the vertical eddies and the alluvial silt by all eddies. Where there is sufficient turbulence to transport bed sand, alluvial silt cannot settle out at all, such that it is absent from the bed material. In 1940, the observations made by Vetter and others were confirmed by EINSTEIN, ANDERSON, and JOHNSON [1940] from the result of actual river measurements, and it is according to their proposal that these two types of load are named bed-material load and wash load respectively. The distinction between these two types of load was further clarified by EINSTEIN and JOHNSON [1950], and the essential features and the significance of this difference has now become well known and widely accepted.

The bed-material load refers to that part of the moving particles which is abundantly available in the bed. The rate of this load is governed primarily by its ability to be moved in the stream channel and bears a definite relationship to the flow. The bed-material load is always transported to its capacity because any surplus or deficiency of the load with respect to the capacity is immediately deposited in or scoured from the bed. Therefore, its rate is the controlling factor in determining the stability of the stream channel.

The wash load refers to that part of the moving particles which is washed through the stream channel without any deposition. It is not found in any significant amount in the bed. The rate at which the wash load is moving through a reach depends only on the rate with which these particles become available in the watershed and not on the ability of the flow to transport them. This state of affairs has been interpreted as a condition under supply, where the supply of these particles is permanently below the capacity of the stream to move them. It is this part of the material, nevertheless, which contributes the bulk of the lake or reservoir deposit.

The difference between these two types of load is thus very well illustrated and readily accepted. However, the following questions still remain to be answered: (1) Are the basic laws which govern the motion of these two types of load different? (2) If the laws are not the same, then what are the differences and what causes the differences? (3) If the laws are the same, then why does there exist in one case a definite relationship between the rate of transport and the discharge, and in the other case not? It is the purpose of this paper to answer these questions.

The bed-load function--In 1950, a complete theory was presented by EINSTEIN [1950] which permits the calculation of the equilibrium rate at which various discharges will transport the different grain sizes of the bed in a given channel. It was concluded on the basis of special experiments that bed load moves in a series of steps of a given average length, and that each grain is periodically deposited in the bed after performing such a step. The number of particles deposited per unit time in the unit of bed area may be expressed in terms of the rate of transport and the size and weight of the particle. The rate at which sediment particles of a certain size are eroded from the bed is proportional to the number of particles in the surface of the bed area and to the probability that such a particle in the bed surface is eroded during the unit time. This probability may be expressed also as the probability of the ratio of dynamic lift on the particle to the weight of the particle under water to be larger than unity. The equilibrium rate of bed-material transportation is then obtained by equating the number of particles deposited on and eroded from the unit bed area per unit time; and this leads to the final bed-load equation

$$1 - (1/\sqrt{\pi}) \int_{-B_* \psi_* - 1/\eta_o}^{B_* \psi_* - 1/\eta_o} e^{-t^2} \, dt = A_* \phi_* / (1 - A_* \phi_*) \quad \ldots\ldots\ldots\ldots (1)$$

in which η_o, A_*, and B_* are universal constants. The equation is represented graphically in Figure 1 by a single curve between the flow intensity ψ_* and the intensity of bed-load transport ϕ_*, in which

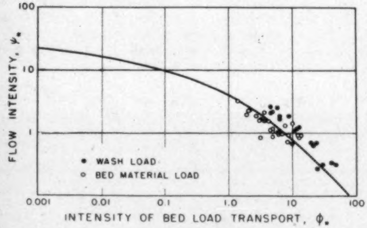

Fig. 1--Relationship of ϕ_* to ψ_*

$$\phi_* = (i_B/i_b)\, \phi = (i_B/i_b)\,(q_B/\rho_s g)\, [\rho_f/(\rho_s - \rho_f)]^{1/2}\, (1/gD^3)^{1/2} \quad \ldots\ldots (2)$$

$$\psi_* = \xi Y (\beta/\beta_X)^2 \psi = \xi Y (\log_{10} 10.6/\log_{10} 10.6\, X/\Delta)^2 [(\rho_s - \rho_f)/\rho_f](D/R' S_e) \quad \ldots\ldots\ldots (3)$$

where

i_B = fraction of bed load in a given grain size
i_b = fraction of bed material in a given grain size
q_B = bed-load rate in weight per unit of time and width
ρ_f, ρ_s = density of the fluid and solids, respectively
D = grain size
R′ = hydraulic radius with respect to the grain
S_e = energy gradient
Δ = the apparent roughness diameter
X = characteristic grain size of mixture
Y = pressure correction in transition smooth-rough
ξ = "hiding factor" of grains in a mixture

The intensity of bed-load transport, ϕ_*, depends not only on the rate of sediment motion, but also on the composition of the material in the bed. The bed-load function as given by (1), therefore, actually indicates an interrelationship between the rate of transport, the flow, and the bed composition.

Equations (1) to (3) are derived from experiments with uniform sediment. However, they have such a form that they can be applied equally well to the individual grain sizes of sediment mixtures, where the correction factors ξ and Y assume values different from unity. These two correction factors are derived from a set of 26 experiments conducted during the years 1944-1946 at the California Institute of Technology by EINSTEIN [1950]. In these experiments the spread of the particle sizes in the mixtures is relatively small and the bed material still acts more or less as a unit. The segregation of the bed material in the bed is not a serious concern, which justifies the use of the original material as the bed material in the analysis.

In a recent study at the University of California [EINSTEIN and CHIEN, in press], ground quartz of silt sizes is included in the mixtures in large amounts to extend the size range. The bed material then has a strong tendency to segregate. Non-moving particles, if any exist in the bed, and slow-moving particles tend to accumulate in surface layers of the bed during the transport. This segregation of bed material has a strong effect on the transport rate of the various sediment sizes, especially on that of the fine particles. It was also found that when the flow around the grains becomes laminar, the lifting coefficient of these particles is no longer a constant, but changes inversely proportional to the Reynolds number of the grain. With these two generalizations, the applicability of (1) can be extended down to a grain size of ten microns, and the fact that such a generalized bed-load function can be established is taken as the basis of an analysis answering the previously posed questions.

The experiments--One special set of five experiments was conducted to study the behavior of wash load. The amount of material available in the flow was controlled by continuously feeding material into the closed system or by taking the moving particles out from the flow. The mixture used had a wide range of particle sizes from four to 0.005 mm. It was expected that the coarse and the fine fractions of the mixture would behave like bed-material load and wash load, respectively.

In the first three runs, sediment was fed continuously at a slow rate into the flow. During this period the bed grew by deposition of part of the added sediment, while another part, especially the finer grains, continuously moved around the closed system of the flume, increasing the rate of transport progressively. A maximum total-load concentration of 15 pct by weight was reached in Run 3. At that stage of Run 3, the feeding of material was discontinued and the test reach was kept at equilibrium state for five hours. In the next two runs, some water with the suspended particles was siphoned out of the system at the entrance of the flume near the exit of the return pipe and replaced by clean water. Local high turbulence of the flow kept practically all the particles from the return pipe in suspension. The bed was scoured continuously during that operation.

The load was sampled every 30 minutes during the run. This yielded information as to the variation of the transport rate for different particle sizes with time. At the conclusion of each run the flow was stopped and the transported particles were allowed to settle on the bed. The water was drained and the bed-material samples were taken at two different sections in the test reach after the deposited moving particles had carefully been removed. The subsequent layers of bed material were sampled and dried for mechanical analysis. The composition of the topmost bed layer was then correlated with the transport rate and the flow parameters measured near the end of that run by means of the bed-load function for the individual grain sizes.

Experimental results and their interpretation

The division between bed-material load and wash load--In this experiment, three different regimes were maintained so far as the amount of available material is concerned, namely, first, continuously increasing availability, then constant availability, and finally decreasing availability. According to the definition, the transport rate should follow the trend of these stages closely for the wash load, but should remain constant for the bed-material load. This can be used to test if this type of experiment provides the desired information. It also indicates where the change from bed-material load to wash load occurs.

The rate of transport of particles in the different size fractions is plotted against the cumulative duration of experiment for all the three stages in Figures 2 and 3. The various curves in the two graphs are labeled according to sizes of the geometric mean grain size of each fraction. The flow conditions, though varying slightly from run to run, can be regarded as constant for the present.

Figures 2 and 3 clearly indicated that, for particles coarser than 0.1 mm, the rate of transport for each grain size fluctuates around its own average value regardless of whether its availability in the flow is increased, unchanged, or decreased. This part of the material, therefore, behaves like bed-material load. On the other hand, particles smaller than 0.06 mm behave exactly like wash load, as their rates of transport depend entirely on their availability in the flow. Particles finer than 0.1 mm and coarser than 0.06 mm represent a transition between the bed-material load and the wash load.

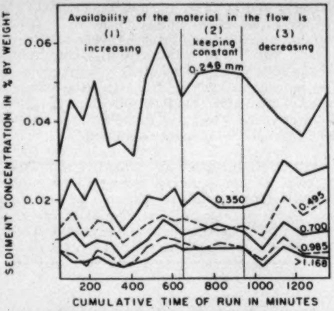

Fig. 2--Variation of load with different availability of material in the flow: coarse fractions (rate of transport for each particle size fluctuates around its own average value regardless of its availability in the flow; all particles behave as bed-material load)

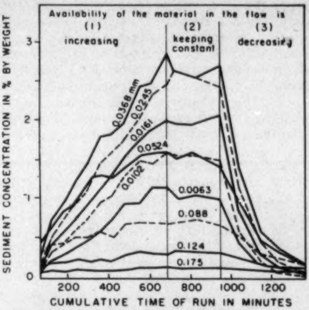

Fig. 3--Variation of load with different availability of material in the flow: medium and fine fractions (particles coarser than 0.10 mm behave like bed-material load; particles finer than 0.06 mm behave like wash load; their rates depend on their availability in the flow)

Knowing which part of the mixture behaves like wash load, we now turn our attention to find out (1) whether the wash-load particles are represented in the bed and (2) what the laws are which govern the motion of wash load.

Bed composition--Figure 4 shows the compositions of the feed material, of the total load, and of different bed layers for Run 1. The topmost layer of the bed is distinctly finer than the bulk of

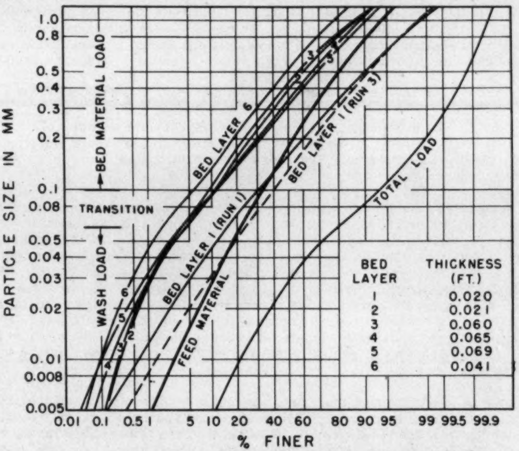

Fig. 4--Compositions of the feed material, of the total load, and of different bed layers (Run 1)

the bed deposit. Although the wash load ($D < 0.06$ mm) constitutes only about five per cent of the bulk of the bed deposit, it constitutes as much as 17 pct in the surface layer of the bed. Furthermore, as the material was continuously fed into the flow, this surface layer not only became finer (as indicated by the composition of the surface layer of Run 3 in the same graph), but its thickness also increased markedly from 0.02 ft in Run 1 to 0.095 ft in Run 3. This clearly contradicts the current belief that the wash load is not significantly represented in the bed. Attention should be called to the fact that this fine surface layer, though sampled after the flow was stopped, did not include any of the particles deposited after the end of the run. The layer formed by the particles in motion was always carefully removed before the fine surface layer was sampled.

While material of all sizes was continuously settling out and building up the bed, this fine layer always managed to stay at the top of the bed. In other words, during the aggradation of the bed, the coarse particles always sank down under the fine surface layer. This can be explained only if the surface layer is not stationary, but rather shifts constantly. With the existence of sand bars on the bed surface, the coarse particles are caught by the eddies behind the crests of the sand dunes and thus accumulate in the lowest points of the bed. The particles on the very surface of the dunes and the dunes themselves both move forward, temporarily covering the newly deposited coarse particles.

This description offers an explanation why the fine grains are found to lack in a river bed. In the first place, this surface layer is extremely difficult to sample. As any sampling device is lowered to the bed during the flow to collect samples of bed material, the water scours into the bed near the device and washes away most of the fine surface layer. If the bed is sampled after the flow, the fine surface layer is disturbed by the receding flows. Furthermore, in practice a river bed is always described at considerable depth and not by a surface layer only. In a non-stratified river bed [EINSTEIN and CHIEN, in press] there are thus only insignificant amounts of fine particles sampled, as described for the lower layers.

The fact that appreciable quantities of the fine particles stay only at the surface layer is important in another respect, too. As this layer is in direct contact with the flow, a slight change of flow or of sediment supply will immediately induce deposition or scour in this layer. For the coarse particles, the bulk of the bed beneath the surface layer acts as a reservoir. Any additional particles deposited into the surface layer will be stored in, and any particles removed from the surface layer will be replaced from the bed beneath. The amount of coarse particles available at the bed surface thus remains almost unchanged. For the fine particles, on the other hand, the change of material due to change of flow is limited mainly to the surface layer itself. The material deposited in the surface layer will be accumulated right there and there will be no further supply from the bed underneath in case part of the surface layer is washed away. In effect, a change of flow or of sediment supply may immediately change the amount of fine particles available at the bed surface. The consequence of this is far-reaching, and will be explained later.

Relationship of ϕ_* to ψ_*--The transport rate of sediment, the composition of the surface-bed layer and the flow are correlated according to the generalized bed-load function, and the result is plotted in Figure 1. The experimental points, despite appreciable scatter, follow the theoretical curve of the relation of ϕ_* to ψ_*. The scatter is caused by all the errors and uncertainties involved in the sampling and analyses of the total load and bed material over the extremely wide range of particle sizes.

The fact that there exists no significant difference between the points of wash load and the points of bed-material load indicates that the laws which govern the motion of these two types of load are the same. This finding also throws some light on the question of transport capacity of a river channel. The stipulation of a transport capacity without reference to the concentration with which a given type of sediment is represented in the alluvial bed is meaningless. Wash load, just like bed-material load, moves in steps near the bed, and is periodically deposited in the bed after completing such a step, even if the duration of rest is small. Part of the material is bound to be found in the bed and its transport capacity depends on the percentage with which it is represented in the bed. Approaching the capacity question for the fine particles of the mixture from this point of view, this study has shown that basically there is no difference between the so-called wash load and the bed-material load.

Relationship between sediment transport rate and flow--The findings of the preceding section do not imply, however, that there exists also a definite relationship between the rate of transport and the flow for the wash load in a river reach, as in the case of bed-material load. In order to understand this, Figure 5 was constructed to show the interrelationships between the transport

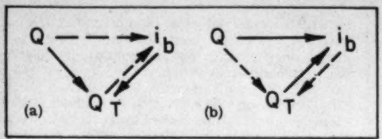

Fig. 5--Schematic figure showing interrelationship among load factors; (a) bed-material load; (b) wash load

rate (denoted by Q_T), the water flow (denoted by Q), and the amount of material available in the bed (denoted by i_b), for both the bed-material load and the wash load. The direction of the arrows in these figures leads from cause to effect; a solid arrow implies a strong and immediate cause-effect relationship, and a dotted arrow means a weak and slow relationship.

Relationshipship of Q to i_b--Considering the supply of bed-material load from upstream remains constant for the time being, then particles settle on the bed when flow is small and scoured from the bed when flow is large. However, since there is an abundance of this kind of material available in the bed, i_b will not be materially affected by changes taking place in the bed due to the variation of the flow.

Wash-load particles are available only at the bed surface in rather limited amounts. A change of flow will cause considerable difference in the amount of this small part of the bed material.

Relationship of i_b to Q_T--For the bed-material load a very large amount of material in the bed supports only a comparatively small fraction of the same material in motion. It is the amount of the material in the bed which controls the amount of the same material in motion.

For the wash load, a very small amount of material in the bed is sufficient to maintain a much larger amount of the same material in motion. It is the amount of material in motion which controls the same material in the bed.

Relationship of Q to Q_T--For the bed-material load, since the amount of material available in the bed is not materially affected by the change of flow and rate of load, i_b can be regarded as a constant, at least for some length of time. This leaves only two variables, Q and Q_T. Therefore, there exists a unique relationship between the rate of transport of bed material load and the flow.

Consider a channel with capacity Q_T under flow conditions Q and bed i_b. Suppose for some reason, the incoming load becomes Q_T' instead of Q_T. Then the bed will be scoured if $Q_T > Q_T'$, and will be built up if $Q_T < Q_T'$ (see Fig. 6). If the reach is long enough for sufficient material to be available in the bed, and if the duration of Q_T' is relatively short, then the temporary degradation or aggradation of the bed will not affect the amount and composition of the bed material to any significant extent. The outgoing load of this reach, therefore, will remain equal to Q_T, the original capacity of the reach. In other words, for a certain flow condition Q, there is only one equilibrium rate Q_T.

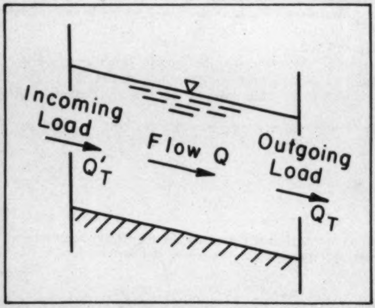

Fig. 6--Relationship between incoming and outgoing bed-material load of a reach of a river

The amount of the wash-load portion of the material available at the bed surface changes with the variation of flow and rate of load. Since there is no way of predicting what this part of the bed material will be at any moment, a unique relationship between flow and rate of transport does not exist unless the supply of such material follows such a relationship for other reasons.

Again, consider a channel for capacity Q_T under flow condition Q and the bed i_b. If the incoming load changes to Q_T' (Fig. 7), then again aggradation or degradation of the bed will result. But in this case the bed composition will change considerably in a short time, adjusting the bed to Q_T'. The outgoing load of this reach will no longer maintain the capacity Q_T of the original bed i_b, but rather assumes a new value Q_T'' which is not much different from the incoming load Q_T'. In other words,

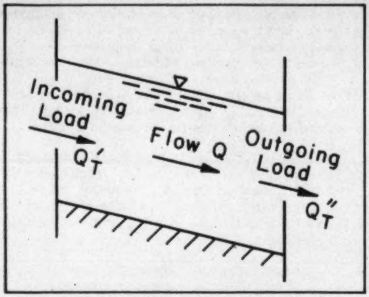

Fig. 7--Relationship between incoming and outgoing wash load of a reach of a river

rate of transport of wash load of this reach not only depends on the flow, but also depends, to a larger degree, upon the material available from the upstream watershed.

Conclusion--The general procedure in computing (or predicting) the sediment rate carried through a stream channel involves the following four steps: (1) Collect all the necessary information concerning the flow and the channel geometry. (2) Take a representative sample of the bed material and determine its composition. (3) From the geometric boundary of the channel and the bed composition, determine the sediment rates for different flows by applying the bed-load function. (4) From the sediment-rating curve and the flow-duration curve, estimate the annual sediment rate carried through the channel section.

In carrying out this type of computation, one fundamental assumption is made, namely, that the bed composition remains unchanged. This is only approximately so for that part of the sediment which is called bed-material load, and is far from the truth for the wash load. From this the answer to the question, Can the rate of wash load be predicted from the bed-load function?, becomes evidently No. Nevertheless, the transport rate of wash load can be calculated according to the bed-load function if the instantaneous bed composition is known. Only, ironically, the bed composition as determined from the instantaneous condition of the channel has no lasting significance so far as the wash load is concerned. We have no way of predicting what the bed composition with respect to the wash load will be, as it depends mainly on the various factors in the upstream watershed which determine the availability of this sediment; and these factors, just like the factors which control the peak and frequency of flood flow, are not subject to quantitative treatment yet. They can only be analyzed statistically if sufficient information is available.

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SOME MEASUREMENTS OF ABLATION, MELTING, AND SOLAR ABSORPTION ON A GLACIER IN PERU

Wallace E. Howell

Abstract--Ablation, melting, and absorption of solar radiation were measured on a glacier of the Nevado de Huagaruancha in the Eastern Cordillera of Peru. From the results it is inferred that (1) evaporation amounts to about five per cent of the melt; (2) the amount of melt is determined largely by the amount of solar radiation absorbed between onset of thaw in the morning and onset of diurnal cloudiness in the afternoon (with average cloudiness, the melt is about one cm daily, rising to 1.5 cm on unusually sunny days); and (3) darkening of the snow increases melt by increasing absorption of radiation and lengthening the period of melting.

Introduction--In connection with the development of a hydroelectric plant on the Rio Paucartambo, which receives much of its dry-season flow from glaciers in the Eastern Cordillera of Peru, it became desirable to obtain quantitative data indicative of the part played by these glaciers in the hydrology of the river. No data applicable to the high-elevation, low-latitude conditions prevailing there were found in the literature; so it was decided to attempt measurements on one of the glaciers constituting a source of the river.

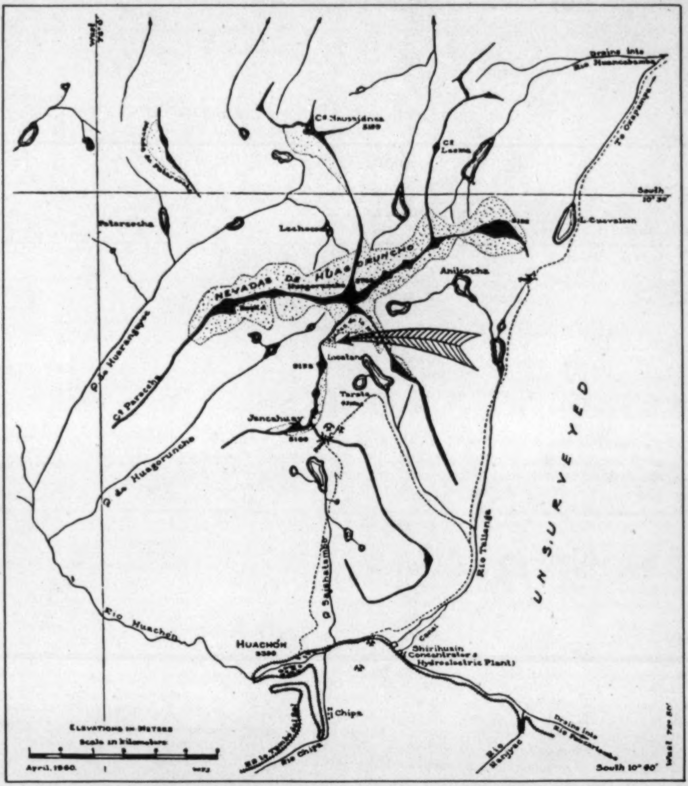
A field trip was made to the area shown on Figure 1, and a base camp was established at the abandoned mining camp of Tarata. After reconnaissance on the surrounding snowfields, the small triangular glacier indicated by the arrow in the map was selected as the site for the measurements, and a camp was established on the rocks next to it. The location of this glacier is shown clearly in the stereoscopic photograph, Figure 2, which shows the main peak of Cerro Huagaruancha as seen from Tarata, with the glacier identified by arrows.

Methods of measurement--Nearly all of the meltwater issuing from the glacier descended along a single channel that branched into two a few hundred feet below the snout of the glacier. Small weirs with triangular notches were placed in the two branches, and hourly measurements made of the flow of water through them.

For measuring ablation and melting on the surface of the glacier, small lysimeters constructed from clear vinylite plastic were used. Each lysimeter was in the form of a shallow bag, ten cm deep and 50 cm square, with a drainage tube fixed in one corner. In use, a square 48.5 cm on a side was marked on the snow surface, with one corner downslope, and a block about ten cm thick was sawn out along the marked lines, leaving the surrounding snow undisturbed except on the downhill corner. The sawn block was placed in the lysimeter and both weighed together on a steelyard having a sensitivity of about two grams. The lysimeter was then placed in the hole from which the block had been cut and the disturbed snow at its foot restored as nearly as possible to its original condition. This procedure was carried out early in the morning, well before the first thawing, while the snow was firm and easily handled. At the end of the period of observation, the lysimeters were again removed and weighed with the snowblocks in them. Figure 3 shows two lysimeters newly set in place near the top of the glacier; in the background is the tent used to shelter the steelyard during weighings.

During the first set of measurements, the drainage tubes were closed with clips and opened periodically to drain the accumulated meltwater into a glass graduate for measuring. However, trouble was experienced with leakage and the clips proved difficult to manipulate, so on the second day the tubes were left open and small containers were buried in the snow to catch the drip between measuring rounds.

Illumination and reflectivity were measured with two ordinary photoelectric exposure meters, one of which was equipped with an incident light attachment. Differences of reflectivity between different portions of the snow surface were measured by taking pairs of simultaneous readings, alternating the meters at the two stations. Measurements of albedo were made by using the incident light attachment, pointing the meter alternately directly at and directly away from the snow surface.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Tarata
Jancahuay
5100
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Cº Paracchu
Q. de Huagoruncho
Q. Sajahalambo
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Canal
Shirihuain (Concentrator & Hydroelectric Plant)
Chipa
Rio Chipa
Rio Manjyac
Drains into Rio Paucartambo
Elevations in Meters
Scale in kilometers
April, 1950
South 10°30'
West 75°30'

Fig. 1--Map of the Huagaruancha massif in central Peru after Jenks; the glacier on which measurements were carried out is indicated by the arrow

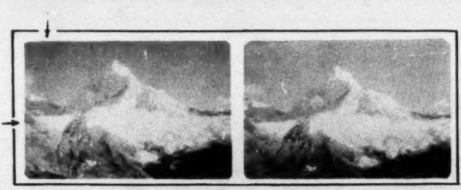

Fig. 2--Stereograph of Cerro Huagaruancha as seen from Tarata; the glacier on which measurements were carried out is indicated by the arrows

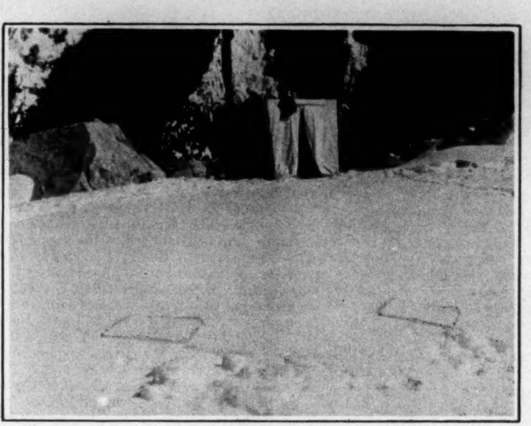

Fig. 3--Two lysimeters in position for measurements of ablation and melting on October 11

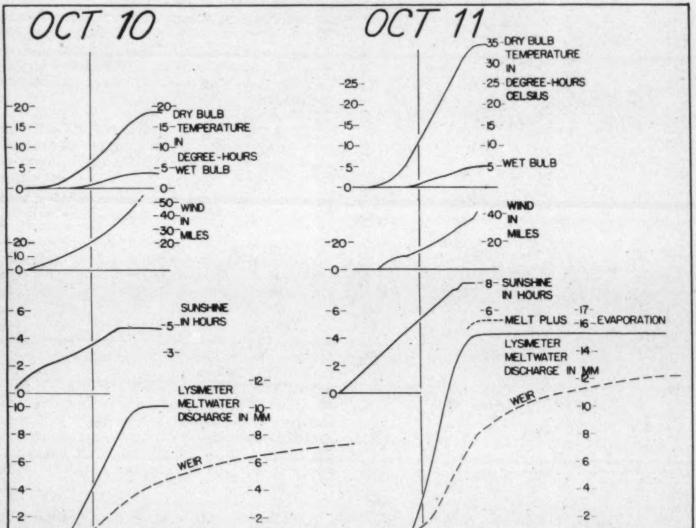

Fig. 4--Synoptic diagram showing the course of several meteorological elements and of melting and stream discharge on October 10 and 11, 1952; the elements are indicated cumulatively from 07h 00m, 75th meridian time

Meteorological observations made during the course of the measurements included hourly observations of wind direction and speed, air temperature and humidity, type and amount of cloudiness, and duration of sunshine. Wind speed was measured with a three-cup anemometer placed 60 cm above the snow surface, and wet- and dry-bulb temperatures with a sling psychrometer; other observations were made without instruments. Occasionally temperature measurements were made at and just below the surface of the snow.

The area of the glacier was measured approximately by making a traverse around it with a steel tape.

Program of observations--Observations on the glacier were made on two days, October 10 and 11, 1952. Observations of stream discharge below the glacier were begun on October 9 and continued through 07h 00m of October 12. On October 10, six lysimeters were laid out in two fields of three each, the fields having as nearly as possible identical slopes and exposures. As soon as the lysimeters had been laid out, one of the fields was artificially darkened by scattering four kg of soft-coal screenings with a sieve over an area measuring four by eight meters. From time to time the meltwater accumulating in the lysimeters was drained and measured and the lysimeters weighed, and the difference of reflectivity between the darkened and undarkened snow was measured. Some of the lysimeters were left in position at the end of the day and weighed again early on the following morning.

On October 11, seven lysimeters were laid out in three fields having exposures selected to be representative of the glacier as a whole, except that the working conditions made it impractical to select a field sloping as steeply as most of the glacier. None of the fields was artificially darkened, but the third field, with two lysimeters, had received a small amount of coal dust that drifted with the wind during the spreading of it the day previous. After thawing began, the contents of the drainage containers were measured in rotation at short intervals until melting ceased for the day, at which time the lysimeters were again weighed. Measurements of the albedo of the snow surface were also made at longer intervals during the day.

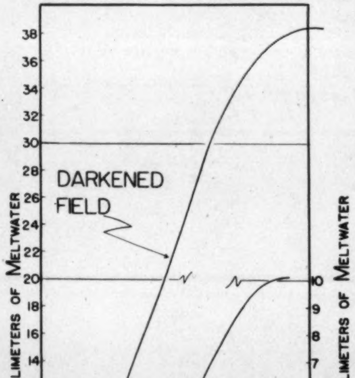

Fig. 5--Comparison of meltwater discharge from lysimeters exposed simultaneously in a snowfield darkened with coal screenings and in an undarkened snowfield

Results of observations--Of the six lysimeters laid out on October 10, two in the undarkened field were found to be leaky, and in two in the darkened field so much snow melted that the bottoms of the lysimeters were bared. In the darkened field, ablation was so rapid that by mid-afternoon the three lysimeters were left sitting atop the snow. On the following day, no difficulties were experienced with any of the seven lysimeters laid out except for a small amount of spillage from one of the collecting containers on one occasion.

The results of the observations are summarized in Figures 4 and 5. These figures show the accumulated values of the several quantities measured over the two consecutive 24-hour periods beginning at 07h 00m October 10, 1952. The melt observed in the field of darkened snow is shown separately in Figure 5 and in this Figure the curve representing melt in the untreated field on the same day is shown for comparison. Comment on these observations will be reserved to the following a paragraph.

On October 11, measurements of the albedo of the snow were made at three different hours. The average value of the albedo was found to be 70 pct, and there was no significant variation of the albedo with the time of day. The albedo of the patch of snow that had been darkened with coal screenings was observed as shown in Table 1.

Table 1--Albedo of the darkened areas

Date	Time	Albedo
1952	h m	pct
Oct. 10	08 45	10.6
	11 00	23.0
11	07 18	23.3
	15 07	28.7

These indicate a steady increase in albedo as melting progressed. It could plainly be seen that the particles of coal tended to gather in small clumps as the snow surface on which they lay slumped in melting. A late stage of this clumping is shown in Figure 6, which is a photograph of a portion of the darkened area, taken at 11h 00m, October 11, the day after the coal dust was spread. This photograph also shows the depression in the snow caused by the faster melting in the darkened area; the surface at that time lay about eight inches below the surroundings, and the clean snow left where a block had been cut out on the first day and placed in a lysimeter was left as a pedestal standing up about four inches high.

Fig. 6--A portion of the darkened snowfield as it appeared at noon, October 11, the day after the field was darkened with coal screenings; the pedestal is the undarkened snow left beneath one of the snowblocks cut and placed in a lysimeter on the previous day

Discussion of results--In a typical diurnal cycle, as illustrated in Figure 4, several hours of sunshine were required to warm the snow, which froze hard during the night, before any melting began on the surface of the glacier. Once begun, melting proceeded rapidly as long as the Sun shone, but stopped abruptly when clouds covered the Sun. The stream discharge shows a slow increase soon after sunrise, probably due to melting of ice frozen during the night on rocks along the stream channel and perhaps partly to rapid melting of a slight fall of graupel that had occurred during the night. A rapid increase follows shortly on the beginning of melting in the lysimeters, and the flow tapers off more or less exponentially after the cessation of melting, with a logarithmic recession time constant of approximately three hours, until the low nocturnal level of flow is reached that probably represents infiltration of groundwater.

Quantitatively, there is a considerable discrepancy between the rate of melting determined from the streamflow and that determined from the lysimeters. There are several sources of error to be considered in explaining the discrepancy. First, there is the ever-present loss due to filtration of water around and under the weirs, a loss that was conservatively estimated by the hydrologist to be ten per cent. Secondly, the lysimeters did not conform to the average slope of the glacier, as explained earlier, and faced the Sun more directly during the hours of most rapid melting than did the rest of the glacier. Thirdly, the lysimeters themselves introduced error, since it could be observed that some additional melting was taking place immediately adjacent to the sidewalls of the plastic bags, causing the snow to retreat about a centimeter from the sidewalls, and indicating that there was some additional absorption of radiation by the plastic that was passed on to the snow in the form of heat. Finally, the one lysimeter on October 10 that did not leak was allowed to fill with water to an extent that probably affected its albedo; the two leaky lysimeters showed 15.5 pct less weight loss than the one on which the curve of Figure 4 is based. When allowance is made for these errors, the results appear consistent within reasonable limits.

As a further check, the rate of melting was computed on the assumption that it was due wholly to absorption of 30 pct (albedo of 0.70) of the estimated solar radiation of 1.89 cal cm^{-2} min^{-1}. This calculation yields a melting rate of 0.0071 cm of water per minute, while the maximum rate of melting obtained by taking the steepest fitted tangent on the chart, Figure 4, is equivalent to 0.0069 cm per minute.

One interesting result of the measurements is the conclusion that the loss of water through evaporation is only about five per cent of the melt. This result is in accord, actually, with the rather slight wind movement and the small amount by which the freezing temperature exceeded the dew point of the air (the wet- and dry-bulb temperatures shown in Figure 4 yield dew points in the range from -4 to -2°C during the period of active melting). It is apparent from this conclusion that the formation of nieves penitentes in high-altitude, low-latitude localities cannot be explained by evaporative processes.

Finally, in view of the close correspondence between the absorption and melting found for the natural snow surface, it is of interest to compare the melting rate with the absorption of radiation for the darkened areas also. A comparison between the darkened and undarkened fields for that day shows the rates of melting during the time of most active melting to be in the ratio of 2.70:1, while at the same time the ratio between the absorptivities of the darkened and unaltered snow was 2.75:1. The ratio of total melt in the darkened field to total melt in the undarkened field, however, is 3.48:1. The melting rate then is increased in proportion to the absorptivity, but the total melt increases in greater proportion. This greater increase results from the earlier hour at which melting starts in the darkened area. The darkened snow was observed in a thawing state an hour and a half earlier than the undarkened snow.

Conclusions--At the season when the glacier was visited, early in the period of accumulation, the snow surface was relatively fresh and clean, and its albedo was 70 pct. Melting on the glacier amounted to about 1.0 to 1.5 cm of water daily, the amount depending upon the duration of sunshine and corresponding closely to the absorption of solar radiation energy. Evaporation losses amounted to only about five per cent of the melt. By darkening the snow with coal screenings, melting was increased in greater proportion than the absorptivity of the snow through increasing the duration of the daily period of melting.

Acknowledgments--The field trip to Huagaruancha was made possible through the sponsorship of the Cerro de Pasco Corporation, and acknowledgment is due to Luis Gallini, hydrologist in the Hydroelectric Department of the Cerro de Pasco Corporation, for the data and information pertaining to streamflow. The assistance of Robert B. Smith in making meteorological and other observations is greatly appreciated. Thanks are due to William F. Jenks for the use of his map of the Huagaruancha massif.

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STATIONARY WAVES IN WATER FLOWING OVER A ROUGH SURFACE

Chia-Shun Yih

Abstract--Stationary waves at the surface of a stream due to a two-dimensional roughness of small amplitude at the bottom are investigated. Results similar to those of Kelvin for one-dimensional roughness are obtained.

Stationary waves in flowing water due to a slight one-dimensional corrugation at the bottom of a stream were investigated by Kelvin [THOMSON, 1886; 1887]. He found that depending on whether the general velocity of flow is greater or smaller than the celerity of propagation of infinitesimal waves with the same wave length as the corrugation, the surface undulations are correspondingly in phase or out of phase by π with the bottom corrugation. In this paper, results similar to those of Kelvin are obtained for stationary waves at the surface of a stream due to a two-dimensional roughness of small amplitude at the bottom. Since the problem encountered is one of truly three-dimensional flow, it seems worthwhile to present the solution.

Assuming irrotational flow, one endeavors to find a potential function which satisfies the Laplace equation and the boundary conditions at the bottom and at the free surface. If the z-axis is vertical and the water is flowing in the x-direction, a representative roughness is given by

$$z = -h + d \cos (2\pi x/\lambda_1) \cos (2\pi y/\lambda_2) \quad \ldots\ldots\ldots\ldots (1)$$

in which y is measured in a direction normal to the x-z plane, h is an effective depth of the stream, d is the amplitude of the bottom roughness, and λ_1 and λ_2 are the wave lengths of the roughness in the x- and y-directions, respectively. It is assumed that d is small compared with h.

If the general velocity of flow of the stream is denoted by U, then the velocity potential can be taken as

$$\phi = U[-x + (a \cosh kz + b \sinh kz) \sin mx \cos qy] \quad \ldots\ldots\ldots\ldots (2)$$

in which

$$m = 2\pi/\lambda_1 \qquad q = 2\pi/\lambda_2 \qquad k^2 = m^2 + q^2 \quad \ldots\ldots\ldots\ldots (3)$$

Evidently, the potential function given by (2) satisfies the Laplace equation

$$(\partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2)\phi = 0$$

It remains to determine a and b so that the normal velocity component v_n vanishes at the bottom and at the free surface, and that the pressure at the free surface is zero.

If n denotes the normal distance from the bottom, the cosines of the angles between the direction of n and the three axes are by definition the direction cosines of the bottom surface given by (1). If d is very small compared with λ_1 and λ_2, the quantity

$$R = \sqrt{(\partial z/\partial x)^2 + (\partial z/\partial y)^2 + 1}$$

is approximately equal to 1, and the direction cosines of the bottom are given approximately by

$$\left.\begin{aligned} \cos\alpha &= \partial z/\partial x = -md \sin mx \cos qy \\ \cos\beta &= \partial z/\partial y = -qd \cos mx \sin qy \\ \cos\gamma &= -1 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (4)$$

The boundary condition at the bottom is

$$v_n = v_x \cos \alpha + v_y \cos \beta + v_z \cos\gamma = 0$$

Since the velocity vector $\vec{v} = -\operatorname{grad} \phi$, this can be written

$$v_n = -(\partial\phi/\partial x)\cos \alpha + (\partial\phi/\partial y)\cos \beta + (\partial\phi/\partial z)\cos\gamma = 0 \qquad (5)$$

As a consequence of (2), (4), and (5), one has, at the bottom

$$U(md \sin mx \cos qy) - U(ak \sinh kz + bk \cosh kz) \sin mx \cos qy = 0$$

or, from (1),

$$md + k(a \sinh kh - b \cosh kh) = 0 \qquad (6)$$

if only first-order terms are considered. If the free surface is represented by

$$\zeta = d' \cos mx \cos qy \qquad (7)$$

then by a similar procedure one can show that the condition $v_n = 0$ at the surface yields the relation

$$md' - k(a \sinh kz + b \cosh kz) = 0$$

which becomes, if z is equated to ζ and only first-order terms are considered

$$md' - bk = 0 \qquad (8)$$

Thus d' is of the order of b.

At the free surface the pressure is zero. By the Bernoulli theorem and (2), this condition can be written (to the first order only) as follows:

$$p/\rho = \text{const.} - gz - v^2/2 = \text{const.} - gz + mU^2 (a \cosh kz + b \sinh kz) \cos mx \cos qy = 0$$

which becomes, if ζ is substituted for z at the surface and first-order terms only are considered

$$gbk/m = mc^2 a \qquad (9)$$

From (6) and (9),

$$b = md/[k(\cosh kh - A \sinh kh)] \qquad (10)$$

in which

$$A = gk/m^2 U^2 \qquad (11)$$

Then from (8) and (10)

$$d' = d/(\cosh kh - A \sinh kh) \qquad (12)$$

so that (7) becomes

$$\zeta = d \cos mx \cos qy/(\cosh kh - A \sinh kh) \qquad (13)$$

which is the required equation of the water surface.

It can be seen from (11) and (13) that depending on whether U is greater or smaller than

$$c = \sqrt{gk \tanh kh}/m \qquad (14)$$

the surface undulations are respectively in phase with those at the bottom or reversed with respect to them. If U is near c, the amplitude of the surface undulation calculated from (12) is too large, and the solution fails. The value c given by (14) can thus be considered as a critical value. Moreover, as will be shown in the following paragraph, this critical value is precisely the celerity of waves with wave lengths λ_1 and λ_2 in the x- and y-directions and propagating in the x-direction in still water of depth h.

If the origin is located at the mean level of the water surface, the equation of the level bottom of a stream of depth h is $z = -h$. The potential function again has to satisfy the Laplace equation, but the boundary conditions are now [LAMB, p. 364]

$$[\partial^2\phi/\partial t^2 + g\,\partial\phi/\partial z]_{z=0} = 0 \qquad \text{(condition at free surface)} \ldots\ldots\ldots\ldots (15)$$

$$[\partial\phi/\partial z]_{z=-h} = 0 \qquad \text{(condition at bottom)} \ldots\ldots\ldots\ldots (16)$$

in which t denotes time. The surface displacement from the mean level calculated from the formula

$$\zeta = (1/g)[\partial\phi/\partial t]_{z=0} \ldots\ldots\ldots\ldots (17)$$

should be, for the purpose of the present demonstration, sinusoidal in x and y with wave lengths λ_1 and λ_2, respectively. The potential function that satisfies all these requirements is

$$\phi = B \cosh k(z+h) \sin m(x - c't) \cos qy \ldots\ldots\ldots\ldots (18)$$

if

$$m^2 c'^2 = gk \tanh kh \ldots\ldots\ldots\ldots (19)$$

in which c' is the required celerity of propagation, and m, q, and k were given in (3). It is immediately clear that the c' determined by (19) is precisely the c determined by (14).

If $q = 0$, so that the bottom roughness is one-dimensional, the critical value becomes

$$c_1 = \sqrt{(g \tanh mh)/m} \ldots\ldots\ldots\ldots (20)$$

which is the celerity of propagation of infinitesimal waves of wave length $\lambda_1 = 2\pi/m$ in still water of depth h. This value is in agreement with that given by Kelvin [LAMB, p. 409, 1945]. If $q \neq 0$, the value of c given by (14) is larger than that of c_1 given by (20). This means that waves travel faster if they are broken up.

The solution given by (13) can be generalized, by the use of the Fourier integral, so as to apply to the case in which the roughness of the bottom follows any arbitrary law. Thus, if the bottom surface is given by

$$z = -h + f(x,y) = -h + (1/\pi^2)\int_0^\infty\int_0^\infty dm\,dq \int_{-\infty}^\infty\int_{-\infty}^\infty f(\xi,\eta)\cos m(x-\xi)\cos q(y-\eta)\,d\xi\,d\eta \ldots (21)$$

in which $|f(x,y)|$ is uniformly small and satisfies the usual conditions for representation by a Fourier integral, the displacement of the free surface is obtained by superposition of terms similar to that in (13), due to the various elements of the Fourier integral

$$\zeta = 1/\pi^2 \int_0^\infty\int_0^\infty dm\,dq \int_{-\infty}^\infty\int_{-\infty}^\infty \Big\{[f(\xi,\eta)\cos m(x-\xi)\cos q(y-\eta)]/ [\cosh kh - (gk/m^2 U^2)\sinh kh]\Big\}\,d\xi\,d\eta \ldots\ldots\ldots\ldots (22)$$

The series counterpart (for a periodic f(x, y)) of this result is in particular applicable to the case in which the bed of the stream consists of sand dunes of various shapes, since the movement of the dunes is in general rather slow. It should be noted that if the spectrum of f(x, y) is more than a single pair of values of m and q, the general velocity of flow of the stream can be above the critical for certain pairs of m and q and, at the same time, below the critical for certain other pairs. Thus the simple phase relationships between the surface and the bottom no longer exist. This accounts for the extremely erratic nature of the behavior of the surface of a stream with an irregular bed.

From the foregoing, the following conclusions can be drawn: (a) For a stream-bed with a slight roughness which is sinusoidal in two perpendicular directions, the undulations at the free surface are in phase with those at the bottom if the general velocity of flow is above a critical value given by (14) and are out of phase by π with those at the bottom if the general velocity of flow is below this critical value. (b) The critical velocity defined in the above sense is precisely the same as the celerity of waves with the same wave lengths as the bottom roughness, and propagating longitudinally in still water of the same depth, in the absence of the roughness at the bottom. (c) The critical velocity is increased by the presence of corrugations in the transverse direction (horizontal direction perpendicular to the direction of flow). (d) The surface undulations for a bed of random roughness are obtained from the elemental solution (13) by means of the Fourier integral, and are given by (22). The corresponding result for an arbitrary periodic roughness applies in particular to the case in which the stream-bed consists of sand dunes. However, the simple phase relationships between the surface and the bottom no longer exist if the stream-bed is not simple-harmonic.

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EVALUATION OF SIGNIFICANCE OF SLOPE CHANGES IN DOUBLE-MASS CURVES

L. L. Weiss and W. T. Wilson

Abstract--The double-mass method is commonly used in the interpretation of precipitation records. Interpretation of double-mass curves frequently involves rejection or acceptance of indicated changes in slope. Often, the decision must be based on inadequate station records. In any case, it is important that the analyst should know the probability of getting an abrupt slope change purely by chance. The significance of any slope change can be evaluated by a statistical treatment making use of range instead of standard deviations. The application is simplified by a special protractor and simple nomograph.

Introduction--Double-mass curve is a term used to signify a plot on arithmetic cross-section paper of the accumulated values of one variable versus the accumulated values of another. If the first variable is proportional to the second, these accumulated values plot as a straight line. If the factor of proportionality has one value for the first portion of the series of data and another for the second portion, the plot will appear as a pair of intersecting straight lines. The point of intersection is called the break.

Double-mass curves are often used by hydrologists to adjust or correct precipitation records for changes in gage location, gage environment, or observation procedure when these factors introduce a new factor of proportionality. Their use has been described by MERRIAM [1937] and KOHLER [1949].

Changes in slope of a double-mass curve or breaks are indicated when an appreciable change in trend for the test station A occurs without a simultaneous corresponding change in trend for the associated reference, or base, station or stations.

Inspection of station histories shows that some breaks can be associated with changes in gage location, gage environment, or observation procedure. However, breaks which cannot be so associated are also sometimes found. In either case, it is necessary to determine whether the indicated break is of sufficient significance to justify a broken double-mass curve. Obviously, the evaluation of significance must be based on statistical considerations of the precipitation record itself. For practical use, the evaluation procedure must be in the form of a few straighforward, simple rules, based on sound statistical reasoning.

Evaluation procedures--The problem is to decide whether there is a significant difference between the mean slope for the period of the record before the indicated break and the mean slope for the period following, taking into consideration the variation of the individual slopes between successive points in each period about the mean slope for the period. The analysis-of-variance technique is used. In this technique the variations mentioned are compared by computing standard deviations and comparing the variance ratio to a particular value in a standard F-table. For small samples, the range is an efficient measure of the standard deviation. Copies of the F-table and discussions of the range as a measure of dispersion may be found in statistical textbooks, such as by DIXON and MASSEY [1952, pp. 238-245]. This relationship is used here. The ratio which results for the test purpose is the sum of the squares of the range of slopes between successive points in the two periods adjusted for number of points in each period, divided into the square of the difference of the mean slopes of the periods. For significance, this ratio must be greater than a number D, which is determined by (1) the number of points (years) in each period, (2) the significance level of reference, and (3) the appropriate value from an F-table.

Example--An example illustrating the judging of significance of breaks in double-mass curves is given in Table 1, which gives the basic data used in the sample double-mass curve of Figure 1.

The accumulated values for the station are plotted against the accumulated values for the base in the figure. The double-mass curve is shown by a heavy line. A break between 1946 and 1947 appears near the center of the double-mass curve.

Table 1--Basic data for double-mass curve analysis of Figure 1

Point	Year	Station	Accumulated	Base	Accumulated	Station/base
1	1950	7	7	4	4	1.75
2	1949	10	17	4	8	2.50
3	1948	7	24	7	15	1.00
4	1947	11	35	5	20	2.20
5	1946	3.3	38.3	5	25	0.66
6	1945	5.7	44	6	31	0.95
7	1944	2	46	9	40	0.22
8	1943	7	53	8	48	0.88

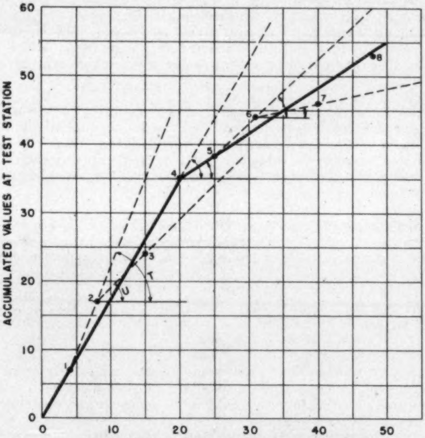

Fig. 1--Double-mass curve analysis illustrating elements used in evaluating change in slope

Nomograph--The analysis is accomplished by use of a nomograph. The arguments of the nomograph are obtained as follows. Draw the lines between the successive points for each side of the break that have the greatest and least slopes. These are shown as dotted lines in Figure 1. One pair intersects at point 2, defining the angles T and U. The slopes of each of these intersecting lines are obtained by means of a special transparent protractor (Fig. 2), labeled in terms of tangents of angles, which are used as follows. The tangent of angle U is subtracted from that of angle T to obtain A′ = 1.50. Do likewise at point 6 to obtain B′ = 0.73, and likewise at point 4 for C = 1.08. Then, with n = 4 for both portions of the curve, on the auxiliary portion of the nomograph (Fig. 3) adjust A′ to A = 1.35 and B′ to B = 0.66; then in the main portion of the nomograph (Fig. 4), with a straight edge set at these values of A and B on the corresponding scales, read the value 2.26 at the intersection of the straight edge and the intermediate scale. Set the straight edge on the point just determined and the C value (1.08) on the C scale, and read the value 0.52 at the intersection with the D scale. This example is illustrated by the dashed lines in Figure 4. Comparing this value with the table of D, it is seen that for the sum of the 4 points on each side of the break, that is, s = 8, D = 0.52. The probability level is about four per cent.

The levels of significance obtained by this method are subject to the bias inherent in any departure of the precipitation population from normality and from the fact that the segments of double-mass curves subjected to test are selected rather than randomly chosen. These and other sources of bias would be difficult to evaluate. As a practical and objective tool the method will be used to gain some perspective in classifying breaks that have been made and relating the quality of the results to the measures of fiducial limits. It is not known what proportion of Type I to Type II errors should be sought (a Type I error occurs if the break is significant but the test indicates it is not; Type II if the break is not significant but the test indicates it is), so it seems useful to use this method as a comparative scale, even if the absolute values of the levels of significance may not be correct. The final judgment will have to be empirical, in terms of useful measures, regardless of whether they are absolute or relative.

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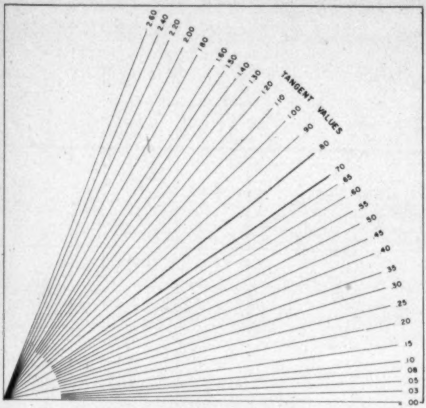
TANGENT VALUES
2.60
2.40
2.20
2.00
1.80
1.60
1.50
1.40
1.30
1.20
1.10
1.00
90
80
70
.65
.60
55
50
.45
40
35
.30
.25
20
15
.10
08
05
03
00

Fig. 2--Template for measuring tangents of angles

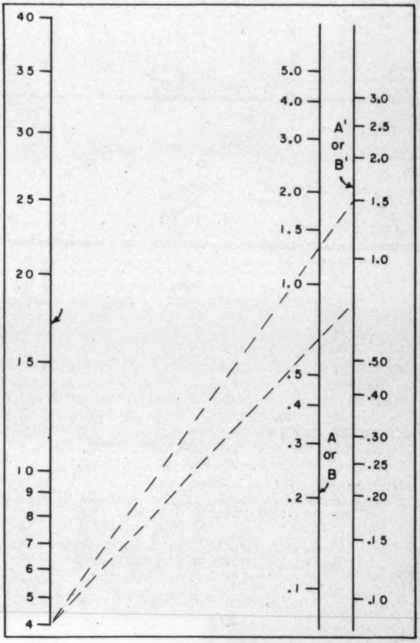

Fig. 3--Auxiliary portion of nomograph for adjusting A' and B' values by taking into account the number of points

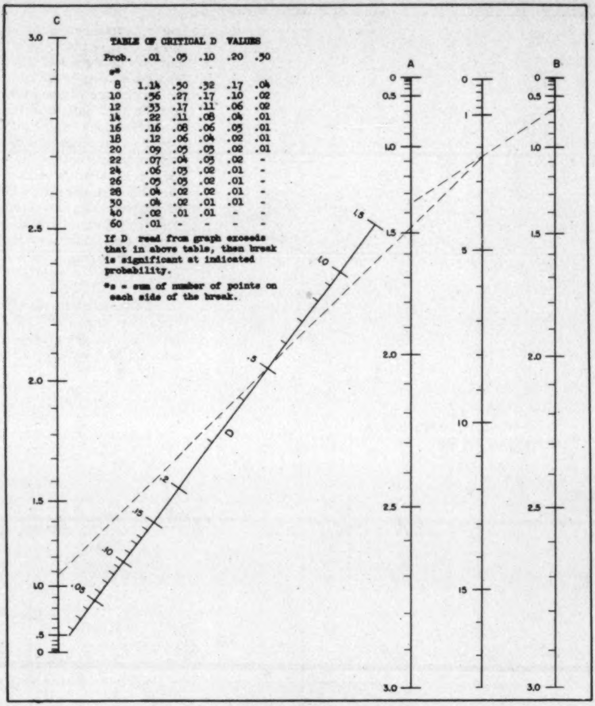

TABLE OF CRITICAL D VALUES

Prob. s*	.01	.05	.10	.20	.50
8	1.14	.50	.32	.17	.04
10	.56	.27	.17	.10	.02
12	.33	.17	.11	.06	.02
14	.22	.11	.08	.04	.01
16	.16	.08	.06	.05	.01
18	.12	.06	.04	.02	.01
20	.09	.05	.05	.02	.01
22	.07	.04	.05	.02	-
24	.06	.05	.02	.01	-
26	.05	.05	.02	.01	-
28	.04	.02	.02	.01	-
30	.04	.02	.01	.01	-
40	.02	.01	.01	-	-
60	.01	-	-	-	-

If D read from graph exceeds that in above table, then break is significant at indicated probability.

*s = sum of number of points on each side of the break.

Fig. 4--Nomograph for evaluating significance of breaks in double-mass curve

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STREAM-FLOW FREQUENCY DISTRIBUTIONS IN CALIFORNIA

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Abstract--The flow-duration curve as a means of expressing stream-flow distribution is briefly described together with its applications and construction. Flow-duration curves were prepared for a selected group of ten California streams. The shapes of these curves are discussed in relation to the prevailing basin and climatic conditions. To clarify further the analysis, frequency curves in the form of histograms were plotted. The usefulness of the frequency curve over the flow-duration curve for analytical purposes and the need for further study are emphasized.

Introduction--The flow-duration curve is generally recognized as the most suitable means of expressing the distribution of discharges of a stream if their sequence is unimportant. This curve, plotted on coordinates of discharge versus per cent of time, has been widely used in studies concerned with stream flow [BEARD, 1943; LIEBERMAN and HOOVER, 1951]. Analyses of flow-duration curves have been made by SAVILLE and WATSON [1933], FOSTER [1934], and MORGAN [1936]. Straight-line plotting of duration curves was studied by HARRIS [1932] based on the work of GOODRICH [1927] on skew distributions.

The purpose of this study was to investigate the stream-flow distribution of several California streams in order to obtain information as to the types of distributions that existed, the factors which affected these distributions, and the feasibility of developing the distribution of discharges on a stream where no discharge records, or only very short periods of record, were available. Very little fundamental work has been done with regard to the first item. Most studies have been concerned with the determination of flow-duration curves, their general shapes, and their approximations to a linear relationship for particular choices of coordinates. In California, HALL [1921], MALTZMAN [1943], and TROXELL and STAFFORD [1949] have contributed material related to the present study. Hydrologists are in general agreement as to the basic factors which affect stream-flow distribution. Thus, LANE and LEI [1950] listed the following: topography, tributary pattern, geologic structure, soil, vegetation, and meteorological conditions. These factors undoubtedly include all of the key variables involved; however, any attempt to evaluate them all quantitatively in order to ascertain their functional relationships to stream-flow distribution usually becomes a laborious and extremely complex study. Frequently lack of sufficient quantities of accurate data limit the extent of such investigations. The third item to be investigated was an attempt to answer the practical problem of stream-flow distribution where few or no discharge records were available. Recent work by MITCHELL [1950] in Illinois and by CROSS and BERNHAGEN [1949] in Ohio have indicated how flow-duration curves may be adjusted from short periods of record to approximate long periods of record. In an extensive study of stream-flow distribution in the eastern part of the United States, LANE and LEI [1950] proposed an "index of stream-flow variability" for estimating the duration curve of stream flow on streams where there are only short or non-existent records. The discussion accompanying their paper, concerning the approximations and limitations of the method for estimation of flow distributions, clearly showed the extent and complexity of the basic problem.

Selection of streams--A small group of streams, representing the major topographic and climatic zones of the State, was desired for study. A careful check of the upstream flow conditions was necessary in order to insure that only natural flows were being measured, since any unnatural flows would be meaningless for the purposes of the study. Another criterion used in the selection process was that of a relatively long period of record. The majority of California discharge records cover relatively short periods of time; hence, to obtain stream-flow distributions which were representative of the long-time flows, only those streams were chosen which had over 17 years of record. The ten streams selected are shown in Table 1 together with data on basin area, gage elevation, mean basin elevation, mean annual precipitation, average daily discharge, per-cent runoff of precipitation, and period of record. The elevation and precipitation data are at best only close estimates taken from isohyetal and topographic maps. Figure 1 shows the geographic locations of the ten gaging stations.

Table 1--Data on ten California streams selected for study

Gaging station	Drainage area	Period of record	Gage elevation	Mean basin elevation	Mean flow	Mean annual basin precipitation	Mean runoff
	sq mi		ft	ft	cfs	inch	pct
Arroyo Seco near Soledad	241	1903-1948	344	3200	174	40	24
Cucamonga Creek near Upland	10.1	1930-1948	2550	5200	9.2	33	38
Fish Creek near Duarte	6.5	1918-1948	1000	3120	4.4	31	30
Huasna River near Santa Maria	119	1931-1948	600	1500	22.5	22	12
Merced River at Kittridge	935	1930, 1932-1947	750	5660	1254	54	33
N. Fk. Kings River near Cliff Camp	174	1922-1948	6150	9300	349	51	52
Salmon River at Somesbar	737	1931-1948	500	4250	1539	64	43
Temecula Creek at Nigger Canyon	319	1924-1948	1350	3160	14.6	15	5
Teneya Creek near Yosemite	47	1913-1948	4000	7500	104	52	57
Thomes Creek at Paskenta	188	1922-1948	600	3300	241	40	43

A certain amount of error is introduced when flow-duration curves based upon different periods and lengths of record are compared. This point has been mentioned in the discussion of the paper by LANE and LEI [1950] and by MITCHELL [1950]. Since the error decreases with increasing length of record, none of the available records were sacrificed to obtain a standard period of record.

Flow-duration curves--The procedure followed in preparing the flow-duration curves was that of counting the number of mean daily discharges, as published in the Water-Supply Papers of the U. S. Geological Survey, falling in predetermined intervals. The discharge values were divided by the published mean discharge value in order to obtain a dimensionless discharge ratio, $Q/\overline{Q}$, for comparative purposes. This ratio was then plotted on the logarithmic ordinate of the flow-duration sheet and the percentages of time were plotted on the probability scale on the abscissa. The curve was then sketched between plotted points.

Logarithmic-probability paper has been widely used for plotting flow-duration curves for two reasons: (1) the logarithmic scale for discharge enables a wide range of discharge values to be plotted on one sheet, and (2) the probability scale tends to reduce the curvature of the line connecting the plotted points. A straight line on these coordinates indicates a logarithmic-normal frequency distribution; that is, the logarithms of the discharge values form a normal frequency distribution [KALINSKE, 1946; CHOW, 1952]. The idea of a straight-line plot on these coordinates has always been attractive to investigators, although very few stream-flow distributions have been found to fit precisely a linear relationship. The approach to linearity may be close if one chooses to neglect the upper and lower ends of the curve. Such practices, however, defeat the purpose of most flow-duration studies, since these ends are essential for finding the distribution of minimum and maximum flows. These extreme flows are frequently the most important, as is the case for minimum flows in pollution control and for maximum flows in sediment transportation.

Figure 2 shows the flow distribution for the three Sierra basins (see Fig. 1); Figure 3, the three South Coastal Basin streams; and Figure 4, the four remaining ungrouped streams. It is interesting to note the general consistency of the Sierra and South Coastal Basin curves. Because the topography and climate within each of these two groups are similar, it is logical that the curves should show similar characteristics. The Sierra streams exhibit a flatter slope in the upper flow ranges than do the South Coastal Basin streams. This difference can be traced to the major causes of high flows in the two regions. In the Sierra the high flows result primarily from snowmelt runoff in the late spring season, which extends ordinarily over a period of several weeks, while the high flows in the South Coastal Basin come from large rainfalls of relatively short duration occurring in the late winter sea-

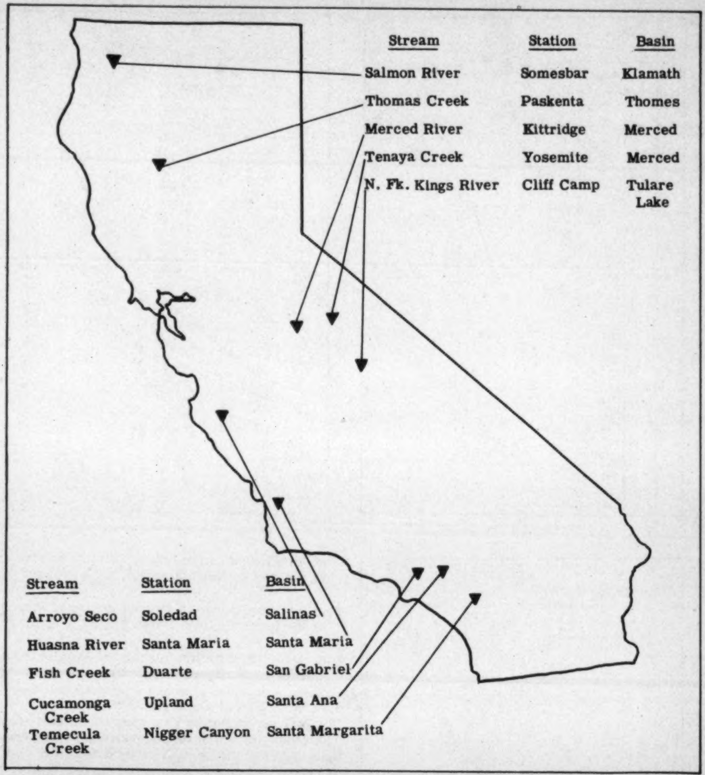
Stream
Station
Basin
Salmon River
Somesbar
Klamath
Thomas Creek
Paskenta
Thomes
Merced River
Kittridge
Merced
Tenaya Creek
Yosemite
Merced
N. Fk. Kings River
Cliff Camp
Tulare Lake
Stream
Station
Basin
Arroyo Seco
Soledad
Salinas
Huasna River
Santa Maria
Santa Maria
Fish Creek
Duarte
San Gabriel
Cucamonga Creek
Upland
Santa Ana
Temecula Creek
Nigger Canyon
Santa Margarita

Fig. 1--Map of California showing locations of ten gaging stations selected for study

son. Thus high flows for a short period of time will be reflected in a steeper slope in the upper portion of the flow-duration curve, and those extending over a longer period of time will form a flatter slope.

The range of discharge of a stream, or the variability of stream flow, is governed by the hydrologic factors controlling the maximum flows, as already discussed, and by the low-flow conditions. The shape of the lower end of the flow-duration curve depends upon the ground-water storage capacity of the basin and upon the aquifer transmissibility [CROSS, 1949]. A stream which originates from a basin with large and uniform ground-water contributions to the base flow forms a flattened slope at the lower end of the curve, whereas a stream having smaller or more irregular ground-water flows give a steep slope at the lower end. Of the ten streams tabulated in this study, it can be seen from the flow-duration curves that Fish Creek, Arroyo Seco, Huasna River, and Thomes Creek all show a pronounced steepness in the lower portions. The reason for this is readily apparent from the discharge records. These four streams all have periods of no flow. Since the percentages of time plotted are based on the entire period of record, the curves must steepen and approach

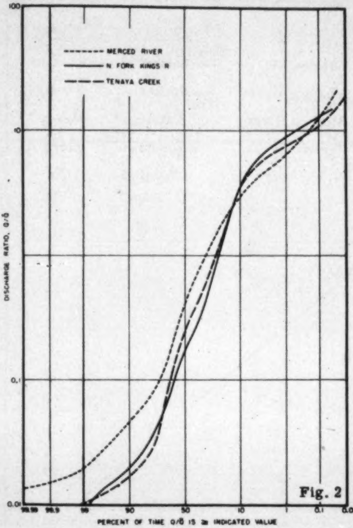

Fig. 2

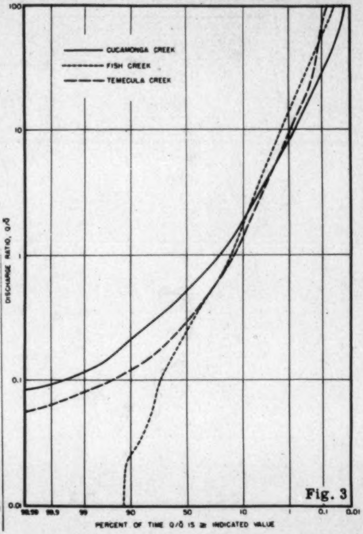

Fig. 3

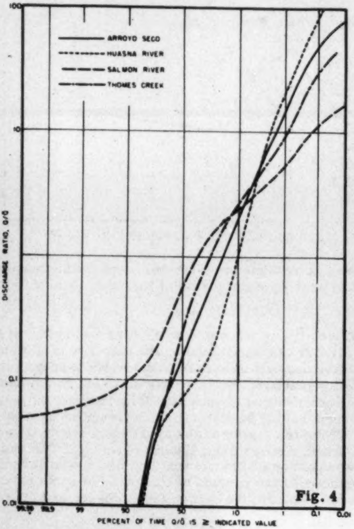

Fig. 4

Fig. 2--Flow-duration curves for three streams in the Sierra Nevada region of California

Fig. 3--Flow-duration curves for three streams in the South Coastal Basin region of California

Fig. 4--Flow-duration curves for four ungrouped California streams

a vertical line on the logarithmic plot as the zero flow values cannot be represented on this scale. The other six streams had mean daily flows greater than zero for all the values included in the period of record; consequently, these curves tend to become horizontal at the lower limit.

It is apparent that the flow-duration curves of these streams do not approximate straight lines on the coordinate systems employed. If a straight-line approximation could be used, then only one point and the slope (which is a function of the standard deviation of the distribution) would be required to define the curve [LANE and LEI, 1950]. In this connection it was found that the percentage of time during which the discharge equalled or exceeded the mean discharge ($Q/\overline{Q} \geq 1$) could be estimated from the mean annual basin precipitation (Fig. 5). Neglecting the scatter of points and the inaccuracies of the precipitation estimates, the relationship's usefulness depends upon similarity of shape of the flow-duration curves. The curves shown

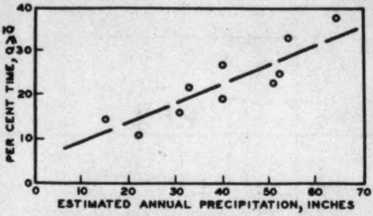

Fig. 5--Relation between mean annual basin precipitation and per cent of time $Q \geq \bar{Q}$

here are not similar; therefore, the estimate from precipitation provides only one point on a flow-duration curve.

Frequency distributions--Because of the different shapes of the flow-duration curves and because the straight-line approximation did not appear valid for California streams, it was decided to clarify the problem by replotting the data in the form of frequency distributions. Since a flow-duration curve is an integral of the more sensitive frequency distribution, it was felt that the various curvatures of the flow-duration curves might be more easily resolved by means of frequency curves.

Frequency curves in the form of histograms were plotted with logarithms of discharge on the abscissa and number of discharges per interval as the ordinate. The intervals selected for classifying the discharges were chosen for convenience and are not of equal width on the logarithmic scale. In order to give a true picture of the data, h_i, the ordinate of the histogram in the i-th interval has been taken to be

$$h_i = (\bar{w}/\bar{w}_i)f_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where w_i is the width of the i-th interval, $\bar{w}$ is the mean interval width, and f_i is the discharge frequency in the i-th interval. This choice of ordinate makes the area under the histogram in the i-th interval proportional to the frequency f_i, as it should be. The area, A, under the histogram is

$$A = \bar{w}\, \Sigma\, f_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Because the intervals were approximately equally spaced on a logarithmic scale, the differences between f_i and h_i in most cases amounted to only a small percentage of the original number of discharges.

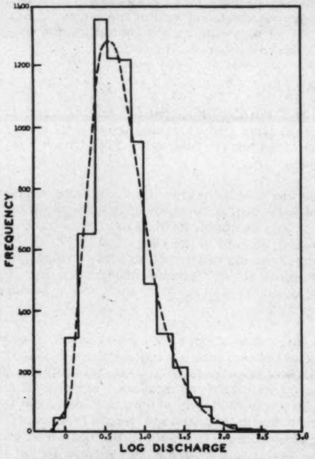

Fig. 6--Histogram of mean daily flow and fitted Pearson type III frequency curve for Cucamonga Creek at Upland

The Cucamonga Creek curve (Fig. 6) even on a logarithmic scale illustrates the common positively skewed distribution frequently encountered in hydrologic data. Thus the lower and higher flows occur relatively infrequently, whereas the most frequent values are those near and below the average discharge. A Pearson type III distribution [PEARSON, 1914; FOSTER, 1924] was fitted to the curve using the method of moments [ELDERTON, 1927]. The general equation is of the form

$$y = y_o\, e^{-px/a}\, (1 + x/a)^p \quad \ldots\ldots \quad (3)$$

where y_o, p, and a are constants depending upon the first three moments about the mean. The expression fitting the observed distribution, taking the origin at the mode, was

$$y = 1280.1\, e^{-5.190x}\, (1 + x/0.74163)^{4.3897} \ldots \quad (4)$$

where y is the discharge frequency and x is the logarithm of discharge. This equation is plotted as the dashed curve in Figure 6. This curve closely follows the observed distribution. If all of the stream-flow distributions had been of this general type, the problem would have reduced itself to a multiple-correlation procedure involving the basin and meteorological parameters and the three constants of (3). Although Temecula

Creek (not shown) had a similar distribution, the remaining California stream distributions could not be approximated by this method and hence this approach to the problem was not feasible.

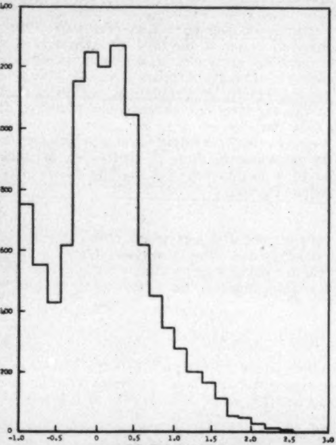

Fig. 7--Histogram of mean daily flows for Fish Creek near Duarte

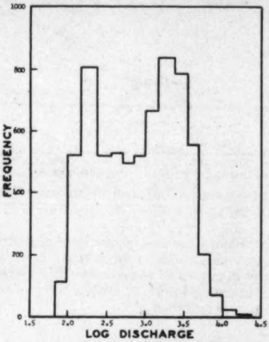

Fig. 8--Histogram of mean daily flows for Salmon River at Somesbar

An excellent example of the limited applicability of the previous analysis method is that of Fish Creek, located less than 20 miles from the Cucamonga Creek gage. The Fish Creek frequency curve, shown in Figure 7, differs from the Cucamonga curve in the distribution of the lower flows. Since Fish Creek reported 320 days with zero mean daily flows, the curve does not approach zero frequency at the lower end of the curve, but instead forms a discontinuity because the zero flow values cannot be shown on the logarithmic discharge scale. Pearsonian frequency distributions derived from the general expression

$$(1/y)\, dy/dx = (x + a)/(b_0 + b_1 x + b_2 x^2) \qquad (5)$$

where a, b_0, b_1, and b_2 are constants, are not suitable for fitting distributions having a positive probability at one point. Such distributions may be separated into parts and treated as a sum of two or more distributions. Such a complex breakdown was not attempted for Fish Creek nor for the similar situations of Huasna River and Arroyo Seco.

The Fish Creek data also may be used to illustrate another point, significance of small discharge measurements. The common inaccuracies of stream flow measurements are well known, but for very small flows other discrepancies appear. For example, in the Fish Creek record nine of the 31 years of record contain mean daily flow measurements in the range 0.01-0.09 cfs, while other years go abruptly from a series of 0.1 cfs measurements to zero flows. Still other years show no flow during dry portions of the year but a footnote states "stream practically dry" for this period. Because of inconsistencies of this sort, no effort was made to analyze the erratic flow distributions found from discharges of this magnitude.

The Salmon River curve (Fig. 8) represents a third type of observed distribution. Because this curve contains two distinct maxima, it cannot be classified into a single Pearsonian distribution. Of the ten streams studied, only this stream showed this particular distribution type. To determine the reason for the two maxima, the discharge values of the maxima were classified by the months in which they occurred. The interval from 150 to 240 cfs, which constitutes the lower maximum, had 72 pct of its discharge values occurring in the three-month period from August through October. It appears then that the primary cause of this maximum is the sustained groundwater flow during this season of the year. As can be seen from Figure 8, the Salmon River at Somesbar reported no zero flows; instead, a well-sustained ground-water flow existed, giving a fairly uniform discharge within the limits of the lower maximum interval. The flat slope on the lower end of the Salmon River flow-duration curve (Fig. 4) indicates a large ground-water storage capacity, but the actual distribution is more clearly revealed by the frequency-distribution curve. The same classification procedure when applied to the upper discharge interval of maximum frequency showed that 88 pct of the values occurred in the first six months of the calendar year and that almost half of these (42 pct) occurred in March and April. Hence the combination of runoff from winter rains supplemented by spring snowmelt runoff is the large contributor to the maximum flows recorded. It is worth noting also that the upper discharge frequencies drop off more rapidly from the maximum in the Salmon River curve than in the Cucamonga and Fish Creek curves. This point illustrates the fact that streams partially governed by snowmelt runoff do not exhibit the wide range of higher flows found in streams controlled primarily by runoff from rainfall.

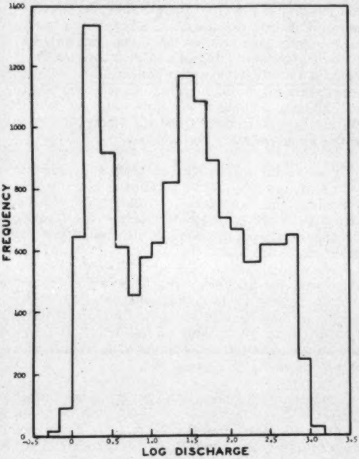

Fig. 9--Histogram of mean daily flows for Tenaya Creek near Yosemite

The Tenaya Creek frequency curve, shown in Figure 9, has been selected from the three Sierra streams to show the distribution type in this region. Here it can be seen that the distribution becomes further complicated with three distinct maxima. The procedure of breaking down the frequencies in the maximum intervals by months of occurrence was employed. The lower discharge-frequency maximum again could be traced to the ground-water contribution, since 60 pct of the discharges in this interval fell in the August-October period. The middle maximum, which includes the median flow, receives some contribution during each month of the year; however, the majority (64 pct) of the values come in the late winter period, January-March. In spite of the high basin elevation and the accompanying low temperatures, flows were recorded continuously throughout the winter seasons and must apparently result from a combination of base flow, occasional rains, and early snowmelt in the basin. The third maximum involving large discharges, stems directly from snowmelt runoff as is readily apparent from the geographic location of the basin. Classifying the three discharge intervals that form this maximum, it was found that 97 pct of the flows occurred in the three-month period, April-June.

Thomes Creek, shown in Figure 10, drains a steep portion of the western side of the Sacramento Valley. As was seen from its flow-duration curve (Fig. 4), the steep lower slope approaching the zero flows was indicative of a relatively

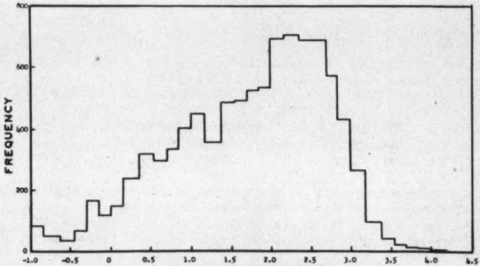

Fig. 10--Histogram of mean daily flows for Thomes Creek at Paskenta low ground-water storage capacity. This characteristic appears in the frequency curve as a uniform decrease of discharge values toward the lower flows. The well-defined ground-water maximum of Salmon River and Tenaya Creek is conspicuously absent. At the frequency maximum 80 pct of the values occurred in the January-May period, coming from the normal runoff from winter rains at the lower elevations and snowmelt runoff at the higher elevations. Note that the higher discharges cover a wider range than those found in Salmon River and Tenaya Creek. This may be traced to a prevalence of discharges resulting from direct runoff of large rainfall durations and intensities.

Discussion--Analysis of results of this study must necessarily be very sketchy. Since only ten streams were investigated, no generalizations are justified. It is apparent nevertheless that analysis of stream-flow data by the methods herein described gives an insight into the general meteorological and hydrologic factors which govern the stream discharges. Many of the interpretations are readily apparent without following the lengthy procedures employed, but only by such detailed methods can quantitative parameters be formulated and applied in estimates of stream flow for other streams lacking long records. It is unfortunate that stream-flow data are not available on punched cards. If so, it would be possible for a small group of investigators to extend a study of this type to a much larger scale and hence be able to evaluate numerous contributing parameters on a basis which would be statistically significant. Until such time, however, considerably slower and more limited analyses of the problem must be followed.

The flow-duration curve is not as versatile a tool as its derivative, the frequency curve, for analytical purposes. In regions having the problem of irregular flow-duration curves in common with California, the changes of slope tend to disguise the important flow distributions, whereas the frequency curve clearly shows these variations in terms of ordinate length. The flow-duration curve is certainly not without its merits. For practical applications, as mentioned previously, it is an extremely useful method of presentation of stream-flow data.

This study serves basically as a good starting point for further work. The various maxima in the frequency curves have been shown to be directly related to the predominance of certain factors during different portions of the year, either from the climatic situation or from the structure of the drainage basin itself. Extending the classification of streams on this basis would permit quantitative evaluations to be made which could be generalized and applied toward preparing estimates of stream-flow distribution for streams having short or no records.

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LEAD ISOTOPIC RATIOS AND GEOLOGIC TIME

Paul E. Damon

Abstract--The consistency of recent data with Nier's data and with the Nier-Holmes hypothesis for the isotopic abundance of common lead ores is examined. It can be shown that, although individual samples deviate markedly from expectation according to age alone, the data taken together are in agreement with the basic hypothesis. The deviations tend to be non-random. Possible causes of these deviations are discussed. One consequence of the Nier-Holmes hypothesis is that the lead ores should have been derived from the granitic rocks of the Earth's crust rather than from a deep-seated source. The study of lead isotopic ratios may be applied to geologic problems other than that of geologic time.

Introduction--NIER [1938, and NIER and Others, 1941], by his work on the isotopic abundance of common ore leads of different ages, has provided the first such data for the determination of the age of the Earth's sialic crust. Calculations based on these data have been made by HOLMES [1946 and 1949], HOUTERMANS [1947], and JEFFREYS [1948]. Recently COLLINS, FARQUHAR, and RUSSELL [1952], and VINOGRADOV, ZADOROJNI'I, and YKOV [1952] have provided new common lead isotope data. Combining their data with Nier's data, COLLINS, FARQUHAR, and RUSSELL [1953] obtain approximately the same values for the age of the Earth's crust (3.5 billion years) and the isotopic constitution of primeval lead as did Holmes. Vinogradov and others, combining their data with Nier's data, obtain a value for the age of the elements of 5.1 billion years which may be compared with the value of 5.5 billion years obtained by Collins and others.

The purpose of this paper is threefold: (1) to examine the consistency of the three sets of data with each other and the theory, (2) to examine deviations from theoretical expectation, and (3) to examine the consequences of theory and measurements with respect to the genesis of lead ore deposits.

The procedure will be: (1) Derive curves, based on Nier's data and Holmes method, for the radiogenic increment to common lead since the formation of the Earth's crust, (2) compare the three sets of data with reference to these curves, (3) examine deviations with regard to accuracy of measurement and departure from the basic assumptions, and (4) derive uranium and thorium abundances and compare these with measured uranium-thorium and lead abundances.

Holmes' solution--Holmes makes the following assumptions:

(a) The isotopic abundance of a sample of lead separated from an ore of age t_m is the same as at the time of ore formation and is representative of the rock lead dispersed at the time of ore formation throughout the part of the crust from which it was extracted and concentrated into ore.

(b) The isotopic abundance of the primeval lead was constant throughout the crust at the time of separation of the sialic material from the body of the Earth, the initial atomic abundances of Pb^{204}, Pb^{206}, Pb^{207}, Pb^{208} being 1, X_o, Y_o, Z_o, respectively.

(c) The corresponding isotopic abundances 1, X_m, Y_m, and Z_m of the isotopes in a sample of ore lead of age t_m are given by

$$X_m = X_o + U_p\,(e^{\lambda_1 t_o} - e^{\lambda_1 t_m}) \qquad (1)$$

$$Y_m = Y_o + V_p\,(e^{\lambda_2 t_o} - e^{\lambda_2 t_m}) \qquad (2)$$

$$Z_m = Z_o + W_p\,(e^{\lambda_3 t_o} - e^{\lambda_3 t_m}) \qquad (3)$$

where U_p, V_p, and W_p (subscripts p and o refer to values at present time and time of formation of Earth's crust, respectively) are the present atomic abundances of U^{238}, U^{235}, Th^{232} in the rock material from which the rock lead was extracted, and λ_1, λ_2, and λ_3 are the respective disintegration constants.

Dividing (1) by (2) and substituting Nier's value of $U_p/V_p = 139$

$$(X_m - X_o)/(Y_m - Y_o) = 139\ (e^{\lambda_1 t_o} - e^{\lambda_1 t_m})/(e^{\lambda_2 t_o} - e^{\lambda_2 t_m}) = (1/r) \quad \ldots\ldots\ldots (4)$$

Using Nier's data in sets of four in (4), Holmes' solution provides $X_o = 10.94$; $Y_o = 13.51$; $Z_o = 29.50$; and $t_o = 3.350 \pm 350$ million years.

The chief criticism of this solution is based upon whether or not assumption (c) is valid. If the lead ore has been subjected to multiple orogeny, there would be changes in the uranium-lead and thorium-lead ratios. As Holmes points out, "The rather scanty geochemical data available suggest that such changes would be quite small and that decreases would be just as likely as increases." Nevertheless, large variations in the regional uranium and thorium content relative to lead would invalidate the equation's use. These equations are doubtless a simplification, but it is interesting to see how well, with certain marked exceptions, Nier's data fit curves based on these equations and Holmes' solution given above.

Calculation of the abundance of uranium, thorium, and radiogenic lead--If in (1), (2), and (3) the primeval lead abundance term is transposed, an expression for the abundance of the radiogenic lead is obtained

$$(X_m - X_o) = U_p\ (e^{\lambda_1 t_o} - e^{\lambda_1 t_m}) \quad \ldots\ldots\ldots (1a)$$

$$(Y_m - Y_o) = V_p\ (e^{\lambda_2 t_o} - e^{\lambda_2 t_m}) \quad \ldots\ldots\ldots (2a)$$

$$(Z_m - Z_o) = W_p\ (e^{\lambda_3 t_o} - e^{\lambda_3 t_m}) \quad \ldots\ldots\ldots (3a)$$

where $(X_m - X_o)$ = RaG abundance, $(Y_m - Y_o)$ = AcD abundance, and $(Z_m - Z_o)$ = ThD abundance.

From Nier's data and Holmes' modal solution, a theoretical curve may be plotted giving the expected ratios of AcD/RaG from (4) for different average times (t_m) for the forming of the lead deposit (Fig. 1). Except for the Austrian and Joplin lead ores, all points fall on or close to the curve.

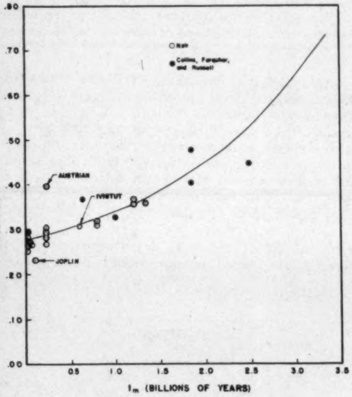

Fig. 1--AcD/RaG ratio for ores of different age of deposition (t_m)

For a deposit formed in recent time ($t_m = o$), the RaG abundance (from Nier's data and Holmes' modal solution) should be very nearly 7.4 and solving (1) for U_p (uranium abundance relative to Pb^{204} for recent time)

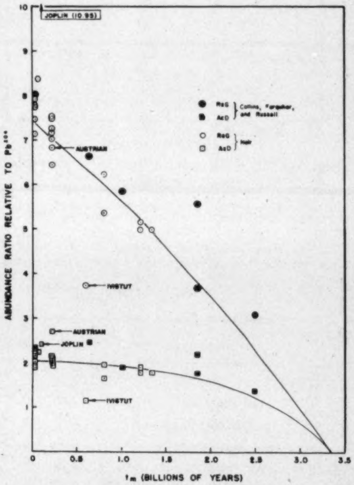

Fig. 2--Abundance of RaG and AcD relative to Pb^{204} for ores of different age of deposition (t_m)

$$U_p = (X_m - X_o)/(e^{\lambda_1 t_o} - 1) = 7.4/e^{(1.53 \times 10^{-10})(3.35 \times 10^9)} - 1 = 11.1 \quad \ldots\ldots (5)$$

The U^{238} content at the time of formation of the Earth's crust (U_o) is given by

$$U_o = U_p + (X_p - X_o) = 7.4 + 11.1 = 18.5 \quad (6)$$

The AcD abundance relative to Pb^{204} for a deposit formed in recent time should be 2.0 and the U^{235} abundance should be 11.1/139. The U^{235} at t_o will be

$$V_o = V_p + (Y_p - Y_o) = 0.1 + 2.0 = 2.1 \quad (7)$$

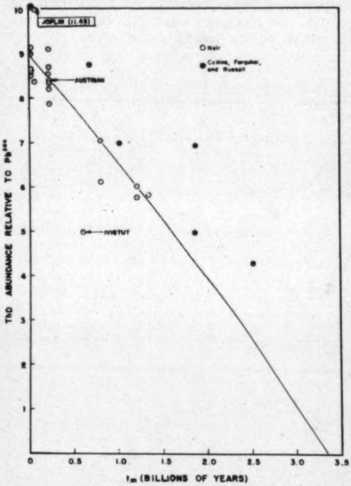

Fig. 3--ThD ratio relative to Pb^{204} for ores of different age of deposition (t_m)

Using the values obtained for U_p and V_p, the theoretical RaG and AcD abundance curves for lead deposits formed at various times (t_m) may be plotted and compared with the individual measurements (Fig. 2).

Similarly, the thorium abundance at the present time (W_p) and at the formation of the Earth's crust (W_o) can be calculated. The ThD abundance curves are given in Figure 3. Table 1 lists the measured abundances. Table 2 lists the theoretical values and the values calculated from measurements of the uranium and thorium abundances in rocks.

It can be seen that except for certain marked exceptions (particularly the Ivigtut, Joplin, and Austrian leads), the majority of points lie on or near the theoretical curves. It is also apparent (Table 2) that the uranium and thorium abundances relative to Pb^{204} and the thorium-uranium ratio (for the Earth's sialic crust) calculated from Nier's data are in reasonable agreement with measured values for acid igneous rocks.

Recent data--The data by COLLINS, FARQUHAR, and RUSSELL [1952] for which geologic ages are given are also plotted in Figures 1, 2, and 3. In Figures 2 and 3 a parallel curve can be drawn which will fit this recent data, whereas in Figure 1 the AcD/RaG ratios fit the curve derived from Nier's data. Although the recent data are in agreement with the basic theory, there appears to be an experimental deviation involving the determination of Pb^{204} but not Pb^{207} or Pb^{206}.

The AcD/RaG ratios for all three sets of data are plotted in Figure 4. A statistical correlation between the theoretical curve and the AcD/RaG values derived from measurement is given in Table 3.

Table 1--Measured uranium-thorium-lead abundance

Rock type	Uranium	Thorium	Th/U ratio	Lead
	g/ton	g/ton		g/ton
Acid igneous	3.0 ± 0.3[a]	13 ± 2[a]	4.4	19[c]
Intermediate igneous	1.4 ± 0.2[a]	4.4 ± 1.2[a]	3.1	. . .
Basic igneous	0.96 ± 0.1[a]	3.9 ± 0.6[a]	4.1	9[c]
Sedimentary	1.2 ± 0.1[a]	3.3 ± 0.7[a]	2.7	. . .
Granitic	3.82[b]	12.48[b]	3.27	16[c]

[a] EVANS and GOODMAN [1941].
[b] SENFTLE and KEEVIL [1947].
[c] SANDELL and GOLDICH [1943].

Table 2--Comparison of calculated and measured uranium-thorium abundance

Item	Calculated from Nier's lead isotope analyses	Measured by Evans and Goodman[a], and Sandell and Goldich[c]		Measured by Senftle and Keevil[b], and Sandell and Goldich[c]
		Basic igneous	Acidic igneous	
Abundance of uranium relative to Pb^{204} in Earth's sialic crust at the present time (U_p)	11.1	6.1	9.0	13.6
Abundance of uranium relative to Pb^{204} in Earth's sialic crust at time of formation (U_o)	18.5	...	...	...
Abundance of actino-uranium relative to Pb^{204} in Earth's sialic crust at time of formation (V_o)	2.1	...	...	...
Abundance of thorium relative to Pb^{204} in Earth's sialic crust at the present time (W_p)	47.5	25.3	40.0	45.6
Abundance of thorium relative to Pb^{204} in Earth's sialic crust at time of formation (W_o)	56.5	...	...	...
Ratio of uranium to thorium at the present time (W_p/U_p)	4.3	4.1	4.4	3.3
Ratio of uranium to thorium at the time of the formation of the Earth's sialic crust (W_o/U_o)	3.1	...	...	...

[a] EVANS and GOODMAN [1941].
[b] SENFTLE and KEEVIL [1947].
[c] SANDELL and GOLDICH [1943].

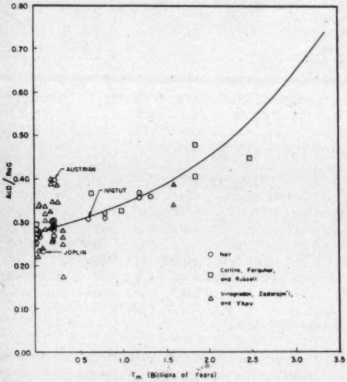

Fig. 4--AcD/RaG ratios for all data

The values of the Russian group show little or no correlation with age of deposition. Nevertheless, the curve drawn provides the best fit to all three sets of data combined. Duplicate results are compared in Table 4. It can be seen that the differences are not small.

Analysis of deviations from the theoretical curves (Table 5) indicate that these deviations are not random.

The author believes that there are three important reasons for the non-random occurrence of an excess or deficiency of all three radiogenic isotopes: (1) Because measurements are relative to Pb^{204}, an error in the determination of Pb^{204} will affect all three radiogenic isotopes in the same way. (2) If the geologic age of the ore is overestimated or underestimated, the radiogenic isotopes will appear to be deficient or in excess. (3) SENFTLE and KEEVIL [1947] have divided North America into ten regions and present the average uranium and thorium content of samples from each region. From their data, it can be shown (Table 6) that when the regional uranium content in acid igneous rocks is high the thorium content also tends to be high.

Ores with anomalous radiogenic lead isotope content--Anomalous radiogenic lead isotope ratios may result from any, or a combination, of the following six causes.

Table 3--Correlation between theoretical curve and measured AcD/RaG ratios

Data and designation	Total number of samples	Correlation coefficient based on AcD/RaG curve	Standard deviation σ	Number samples with deviation $\geqq 2.60\ \sigma$	Number samples with deviation $\geqq$ Joplin ore	Correlation coefficient discarding samples $\geqq 2.60\ \sigma$	Correlation coefficient discarding samples $\geqq$ Joplin ore
Nier (1)	20	0.60	0.031	1	2	0.77	0.84
Collins, Farquhar, and Russell (2)	7	0.59	0.045	0	1	0.59	0.79
Vinogradov, Zadorojni'i, and Ykov (3)	30	0.07	0.052	0	6	0.07	0.49
(1) and (2)	27	0.60	0.035	1	3	0.69	0.80
(1), (2), and (3)	57	0.41	0.045	1	9	0.54	0.59

Table 4--Comparison of duplicate measurements

Ore	AcD/RaG		Difference
	Vinogradov, and others	Nier	
			pct
Nassau	0.302	0.268	12
Saxony	0.291	0.300	3
Joplin	0.214	0.220	3

(1) Variations in the regional U-Th abundances--Ores derived from magmas, the U-Th abundances of which differ markedly from the average for the Earth's crust, will fall above or below the AcD, RaG, ThD radiogenic curves (Fig. 2 and 3). However, the AcD/RaG ratio will not be affected unless the ore has been subjected to multiple orogeny [HOLMES, 1949; ALPHER and HERMAN, 1951] with a marked change in the U-Th abundance within the region. In this latter case the rapid initial production of AcD (Fig. 2) will result in an anomalous AcD/RaG ratio. According to this reasoning the Ivigtut ore 19 (Table 7), the AcD/RaG isotopic age of which is about the same as its geologic age, was derived from a magma of unusually low U-Th abundance.

Table 5--Analysis of deviations from the theoretical curves

Type of error			Estimated random probability of occurrence	Probability of occurrence		
RaG	AcD	ThD		Nier	Collins and others	Vinogradov and others
+	+	+	0.1	0.30	0.67	0.375
..	..	..	0.1	0.35	0.00	0.375
All others			0.8	0.35	0.33	0.250

Table 6--Relative uranium and thorium content of acidic rocks

Uranium and thorium content	Estimated probability	Probability from data of Senftle and Keevil
Both high or both low	0.5	0.8
One high, other low	0.5	0.2

(2) Multiple orogeny with changed U-Th abundance--Holmes has suggested that the anomalous Joplin lead may have passed through more than one orogenic cycle. For instance, this ore could be produced by modification in a source rock with a normal U-Th abundance until 2000 million years ago followed by modification in a source rock with an initial U = 28 and initial W = 82 abundance until the time of ore formation. The AcD/RaG ratio is low, and so the high U, V, and W anomaly must be placed subsequent to a normal or low initial U, V, and W content.

There has been considerable controversy concerning the genesis of the tri-state lead-zinc ore [LINDGREN, 1933]. Those who hold to the theory of a sedimentary origin are divided concerning whether the deposition took place from an ascending or descending solution. A third opinion ascribes the ultimate source to ascending thermal waters of magmatic origin. Considerable support has been given to the hydrothermal argument by the discovery of igneous intrusives of probable Mesozoic age in the Rose Dome area of Kansas and in a well at a depth of 1245 ft at the Bird Dog Mine west of

Table 7--Geologic and isotopic ages of ores analyzed by Nier

Holmes' sample no.	Geologic age according to Holmes	Isotopic age according to this paper	Isotopic age according to McCrady
	10^6 yr	10^6 yr	10^6 yr
1	25	Recent	1500
2	25	Recent	1650
3	25	Recent	1700
4	25 ?	750	1270
5	25	Recent	1840
6	25	100	1550
7	60	Recent	1350
8	60 ?	650	2430
9, 10, 11	100	A	400
12	175	1575[a]	1690
13	220	220	1770
14	220	Recent[b]	1780
15	220	500	2000
16	220	220	1650
17	220	350	1800
18	220	125	1660
19	600	550	2780
20	800	750	2050
21	800	600	2360
22	1200	1325	2350
23	1200	1210	2410
24	Precambrian	1575	2390
25	1330	1250	2400

A = Anomalous; cannot be fitted to radiogenic growth curves or to AcD/RaG isotopic time scale; Joplin ore.

[a] Austrian ore; may have been subjected to more than one orogeny.

[b] Best fit to the radiogenic curves is at about 200 x 10^6 years.

Picher [WEIDMAN, 1932].

If the lead is of hydrothermal origin, it would seem from the argument presented in this paper that the magma from which the lead was concentrated was exceptionally high in its U-Th content. The presence of unusual quantities of helium in the gas fields and radium in brines of Kansas and adjacent states is also of interest in this connection. (P. K. Kuroda of the University of Arkansas has measured radium concentrations in excess of 10^{-10} c/ℓ for Oklahoma brines collected by R. R. Edwards of the University of Arkansas.) At any rate, the origin of the Joplin ore is controversial and its lead isotopic abundance is unusual so that further field and laboratory investigations would be highly desirable.

The high AcD/RaG ratio of the Austrian ore may be explained by modification in a source rock with U = 36 (W normal) until 2500 million years ago followed by modification in a source rock of reduced uranium abundance U = 9 until the present time. (According to Ralph S. Cannon, Jr. of the U. S. Geological Survey (private communication) there is some doubt as to the correct identification of the Austrian ore.)

(3) Age of the ore--The age of the ore must be estimated in most cases by its relationship to the geologic formation with which it is associated or from analysis of included uranium minerals in the igneous rock from which it appears to have been derived. The geologic formation is usually dated indirectly by its stratigraphic position in the geologic time scale. The ages thus determined are only approximate and the possibility of an incorrect correlation is considerable. Furthermore, as pointed out by McCRADY [1952], the isotopic age of an ore of sedimentary origin will not necessarily agree with the age of the enclosing rocks.

The AcD/RaG ratio of an ore is most likely to conform to theoretical expectations since regional variations in uranium abundance will not affect this ratio. It can be seen from Figure 1 and Tables 7 and 8 that there is reasonable agreement between geologic ages and the ages determined from the AcD/RaG ratio of the various ores for Nier's data and for the data of Collins and others. As previously mentioned, the data of the Russian group shows very poor correlation with the age of the

Table 8--Geologic and isotopic ages of ores analyzed by COLLINS, FARQUHAR, and RUSSELL [1952]

Sample no.	Source	Geologic age	AcD/RaG isotopic ratio age
		10^6 yr	10^6 yr
1	Bolivia (galena)	25	350
2	Kengere, Belgium Congo	630	1325
3	Frontenac Co., Ontario, Canada	1000	800
4	Matachewan, Ontario, Canada	. . .	1525
5	Negus Mine, Yellowknife, NWT, Canada	1850	2200
6	Sioux Lookout Galena, Ontario, Canada	2480	2000
7	Rex Property, Great Slave Lake, NWT, Canada	1850	1575
8	Rex Property, Great Slave Lake, NWT, Canada	1850	1680
9	Horseshoe Island, Yellowknife, NWT, Canada	. . .	2275
10	Delhi Township, Ontario, Canada	. . .	1475
11	Garson Mine, Sudbury, Ontario, Canada	. . .	75
12	Worthington Mine, Sudbury, Ontario, Canada	. . .	A
13	Upper Canada Mine, Ontario, Canada	. . .	A
14	Rosetta Mine, Barberton, Transvaal, South Africa	. . .	1975

A = Anomalous; cannot be fitted to radiogenic growth curves of AcD/RaG isotopic time scale.

enclosing rocks.

The isotopic ages proposed by McCRADY [1952] show no agreement with the geologic ages. This is not surprising because his isotopic ages are derived by fitting radiogenic curves to the Joplin and Ivigtut ore which are anomalous. Furthermore, his assumption of an age of 2780 million years for the age of the Ivigtut ore is not warranted because for an ore of this age the AcD/RaG ratio would have to be nearly twice the measured value.

(4) Contamination by local sources of radiogenic lead--Contamination by lead from local radioactive sources resulting in variations in the lead isotopic distribution within deposits is conceivable. However, the Great Bear Lake galena studied by Nier, which is cross cut by pitchblende veins, does not appear to have become contaminated. (Private communication from J. P. Marble, Chairman of the Committee on Measurement of Geologic Time of the National Research Council.)

(5) Fractionation of radiogenic lead isotopes during transport of parent nuclides--The past histories of radiogenic Pb^{206}, Pb^{207}, or Pb^{208} atoms are by no means identical. There are marked differences between the different series in mode of decay, isotopes formed, and the length of time spent in any one elemental form. For instance, the uranium series produces many more long-lived isotopes than do either of the others. In particular, the half life of radon is 3.825 days, whereas thoron and actinon have half lives 54.5 seconds and 3.92 seconds, respectively. This results in the possibility of lengthy transport of radon through such processes as solution, diffusion, and escape into the atmosphere, whereas actinon and thoron have a much more limited range of transport before transmutation.

In some cases the radon may be transported through a lead precipitation zone, whereas starting from the same source Pb^{208} and Pb^{207} already have been formed and are precipitated. The longer life of radon also may contribute to making it more available for water transport by allowing radon sufficient time to diffuse out of the parent mineral. Sample 13 (Table 8) is typical of a lead ore that could have resulted from fractionation of the lead isotopes.

The details of the consequences of the differences between these decay series are quite complex. The point intended to be made here is that fractionation of the lead isotopes is theoretically possible. Whether or not this has actually taken place on a large scale cannot be decided from available data on lead isotopic ratios. More analyses of lead minerals of known sedimentary origin are needed. Also it is desirable to measure the distribution of lead isotopic ratios from point to point within known deposits. The data, as yet, are insufficient for the limits of constancy of lead isotopic ratios within individual deposits to be established.

(6) Variations in the parent magma during deposition--The Nier-Holmes hypothesis tacitly assumes that the lead ore is deposited in a period of time which is so short as to have a negligible effect on the isotope ratios. As the precision of measurement improves, it is possible that this assumption may not be valid. A magma may possibly exist for a significant period of time and its lead isotope distribution may slowly alter due to incorporation of more rock material, loss of original lead isotopes, and the continuous increment of radiogenic lead isotopes from uranium and thorium. The effect should be that lead deposited in the latter stages of the event should be somewhat richer in radiogenic lead isotopes.

Origin of the lead--The hypothesis (assumption a) assumes that the lead ore is representative of the rock lead dispersed at the time of ore formation throughout the part of the crust from which it was extracted and concentrated. If the lead were concentrated from a deep-seated basic source, the calculated value of U_p (Table 2) should be much lower than the value obtained. The calculated value ($U_p = 11.1$) is consistent with the extraction of the lead from the acidic rocks of the Earth's crust and it is indicative of superficial rather than deep-seated origin. SENFTLE and KEEVIL [1947] arrive at the same conclusion.

A conclusion such as this assumes a relatively rapid formation of the Earth's sialic crust. If the continents have been continuously created [WILSON, 1952], this conclusion does not necessarily follow. In fact, the concept of a single age for the Earth's sialic crust also becomes obscure and Holmes' basic assumptions must be reconsidered. The basic equations may still be valid providing the age of the Earth's crust (t_0) is considered as a parameter constant only for specific sections of the crust. From this point of view, it would be necessary to correlate the lead ores on a regional basis.

Concluding remarks--In view of the apparent complexity of Earth history and the experimental errors involved, the agreement between theory and measurement is remarkable (Fig. 4). The deviations from theoretical expectation are non-random and it appears possible to explain the cause of deviations without abandoning or radically modifying the basic theory itself.

Lead isotope ratio studies may in the near future provide information concerning the specific mechanism by which a lead ore has been concentrated and the fundamental orogenetic process itself. It is also quite possible that these ratios may become useful geophysical parameters in the search for fissionable materials. Ores with an exceptionally high content of radiogenic isotopes such as the Joplin ore or the two ores (11 and 12) from Sudbury, Ontario, Canada, if hydrothermal, indicate a magma unusually rich in uranium and thorium, that is, if assumption (c) is valid.

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THE RADIUM CONTENT OF VARVED CLAY

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Abstract--The radium content of varved clays, selected from an exposure of about 470 pairs of beds, has been determined. The results have been calculated for unit mass and unit volume of the dry varve, and unit volume of the varve particles. With one exception the radium content of the winter layer exceeds that of the summer layer. When plotted against time, the radium content shows a periodicity in concentration with no indication of either a general increase or decrease, over the span of years, in the summer layers or the winter layers.

Introduction--While several experimenters have made mechanical and chemical analyses of varved clays which had been deposited in different localities, there has been but one study of any of the radioactive properties of varves that has come to the attention of the authors. This study was made by URRY [1948] and consisted of the measurement of the radium content of a few varves in the clay deposits located at Hartford, Connecticut. These measurements show that the winter portions of the varves contain approximately 1.5×10^{-12} grams of radium per gram of dried varve while the summer deposits contain about two-thirds as much as the winter portions. Also, these measurements indicate that the radium content of the summer layers increased with time while that of the winter layers decreased. The annual weighted radium content for the entire year appears to be nearly constant when calculated in grams of radium per cubic centimeter (cc) wet clay. It was assumed that the results indicated a disturbance in the radioactive equilibrium in the uranium 238 series at the time of deposit.

Since the experiment included the radium concentration of only six varves which were taken from a span of 640 years and since the seasonal and the annual weighted concentrations were expressed in different units, it seemed desirable to make radium measurements on a more complete and distributed set of varves using different modes of expressing the results. In this way it might be determined whether any evidence exists for a lack of radioactive equilibrium at the time the Seattle varves were formed.

For the purpose of comparison, it seems logical to express the numerical values of the radium concentration in three different ways, namely: (a) grams of radium per gram of dry clay, (b) grams of radium per cc of dry clay, and (c) grams of radium per cc of varve particles.

Source of material and geologic background--The varves, the radium content of which is reported in this paper, are exposed in artificial cuts in the vicinity of 12th Avenue and Dearborn Street in Seattle. The geologic background information essential to this study has been provided by J. Hoover Mackin of the Department of Geology at the University of Washington.

The sequence includes about 470 pairs of beds, each consisting of a thicker layer of silty clay and a thinner layer of colloidal clay. The sharp definition of these regularly alternating layers, a generally consistent ratio of about 4:1 in the thickness of the silty clay and the colloidal clay layers, and the presence of rare striated boulders, doubtless ice-rafted, indicates that the pairs of layers are summer and winter deposits formed on the floor of a glacial lake. A few of the units which show marked departures from the normal thickness ratio, or are in other respects unusual, are questionable as yearly deposits.

A more serious question as to the span of years is expressed by the numbering of the varves in separate Series A and B. These series were measured by Mackin (personal communication) in cuts about 1000 ft apart, with the top of the lower (A) exposures corresponding in level with the base of the higher (B) exposures. It has not been possible at this date to correlate directly between the two series, and the time value of the gap between them is therefore not known. The correspondence in level and other relationships suggest that it may be a few years to a few tens of years. The radium measurements reported here include only one varve of Series A. This one is varve A42 in Table 1 and in Figure 1.

On the basis of the stratigraphic relations [HANSEN and MACKIN, 1940] and other factors, it

Table 1--Thickness and radium content of varves

Varve	Thickness	Radium content × 10^{12}			
		Dry varve	Dry varve	Varve particles	Annual average of varve particles
(1)	(2)	(3)	(4)	(5)	(6)
	cm	gm/gm	gm/cc	gm/cc	gm/cc
B305W	0.9	0.53	0.75	1.48	. . .
S	10.3	0.60	0.88	1.66	1.65
B260W	0.8	0.53	0.77	1.52	. . .
S	5.1	0.43	0.62	1.19	1.23
B259W	0.7	0.57	0.82	1.61	. . .
S	2.8	0.45	0.64	1.26	1.33
B258W	0.4	0.52	0.71	1.46	. . .
S	5.0	0.49	0.70	1.37	1.36
B257W	0.3	0.52	0.74	1.46	. . .
S	1.3	0.48	0.68	1.34	1.36
B256W	0.4	0.58	0.83	1.64	. . .
S	2.1	0.48	0.70	1.33	1.38
B255W	0.3	0.51	0.72	1.43	. . .
S	1.9	0.43	0.60	1.19	1.22
B254W	0.4	0.50	0.71	1.42	. . .
S	1.8	0.48	0.69	1.36	1.37
B253W	0.8	0.52	0.72	1.47	. . .
S	18.5	0.51	0.71	1.42	1.42
B252W	0.6	0.52	0.74	1.48	. . .
S	6.0	0.47	0.69	1.30	1.32
B251W	0.9	0.47	0.67	1.34	. . .
S	3.8	0.46	0.66	1.27	1.29
B250W	0.5	0.56	0.83	1.60	. . .
B168W	1.0	0.56	0.79	1.57	. . .
S	6.0	0.48	0.71	1.33	1.36
B101W	2.1	0.53	0.73	1.51	. . .
S	23.0	0.45	0.69	1.33	1.34
B88W	0.7	0.58	0.82	1.65	. . .
S	3.5	0.46	0.66	1.26	1.34
B84W	0.8	0.56	0.79	1.59	. . .
S	2.0	0.48	0.68	1.34	1.41
B83W	0.9	0.52	0.73	1.48	. . .
S	4.4	0.48	0.69	1.34	1.37
B82W	0.8	0.56	0.80	1.59	. . .
S	7.5	0.48	0.70	1.34	1.37
B81W	1.0	0.50	0.71	1.45	. . .
S	3.7	0.48	0.69	1.34	1.36
B80W	1.6	0.55	0.78	1.56	. . .
S	4.5	0.47	0.68	1.31	1.38
B79W	. . .	0.53	0.76	1.50	. . .
A42W	1.8	0.64	0.97	1.83	. . .
S	4.7	0.50	0.73	1.40	1.67

is certain that the varves are pre-Wisconsin in age. It is likely, but not certain, that they were formed during an early Pleistocene glacial stage.

Samples--In securing the samples, it was found necessary to remove a portion of the dried exposed varved clay in order to obtain moist specimens. These moist samples were immediately placed in moisture-tight containers and transported to the laboratory. The density of the moist varves was determined within one or two days after sampling.

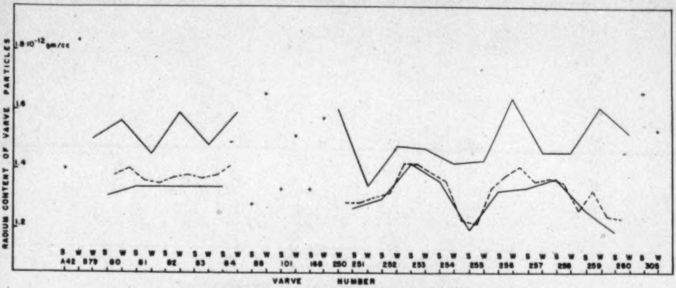

Fig. 1--Radium content of the summer layers, the winter layers, and the annual average of the varve particles

In Series B two consecutive groups of samples were analyzed. These were groups containing varves B79 to B84 inclusive and B250 to B260 inclusive. In addition, varves B88, B101, and B168 were samples in Series B between samples B84 and sample B250. Varve B305 was about ten feet below the top of Series B. Varve A42 is the 75th below the top of Series A and therefore, as indicated earlier, is 75 plus a few years or tens of years older than varve B1 of Series B.

Method of measurement--The density of each summer and winter layer was determined in the laboratory, both in the original moist state and after drying at 120°C until no change in weight occurred. The particle density was determined by the conventional pycnometer method.

The method used for the determination of the radium content was the same as that used by the authors in the analysis of marine sediments [UTTERBACK and SANDERMAN, 1938].

The sample was first dried and ground to pass through a 60-mesh screen. It was then weighed and baked in a furnace for one hour at a temperature of 900° to 1000°C to remove organic matter, water of crystallization, and carbonates. It was then sealed in a glass tube for a period of 30 days or more to insure equilibrium between the radium and radon.

When a determination was to be made, the sample was placed in a graphite crucible vacuum furnace and the furnace and ionization chamber were evacuated. The sample was then heated to approximately 2000° C for a few minutes causing the clay to melt and boil, thus completely removing the radon gas from the sample. The radon was then flushed into the ionization chamber by means of radon-free nitrogen where the ionization produced was measured by means of a photographically recording string electrometer for a period of 24 hours. The apparatus was calibrated with radium standards furnished by the National Bureau of Standards.

Experimental results--The thickness and the radium content of the varves are listed in Table 1.

All of the varves listed in the first column with the exception of varve A42 are numbered in consecutive order, the numbers increasing with decreasing age of the varve.

The relative thickness of the varve layers in the upper part of Series B is shown in the histogram of Figure 2. It will be noted that the summer layers are thicker than the winter layers and in some cases the summer layer is many times the thickness of the adjacent winter layer.

As mentioned in the introduction, the numerical values of the radium content of the varves are expressed in three different ways. These values are listed in Table 1 in columns (3), (4), and (5). The annual average values, calculated from columns (2) and (5), are give in column (6).

Graphs of the different modes of representing the radium content are given in Figures 3 and 4. Curves 3 and 4 in Figure 3 and curve 6 in Figure 4 are plots of the data in columns (3), (4), and (5) respectively of Table 1. It will be observed that there is a periodicity in the radium content of

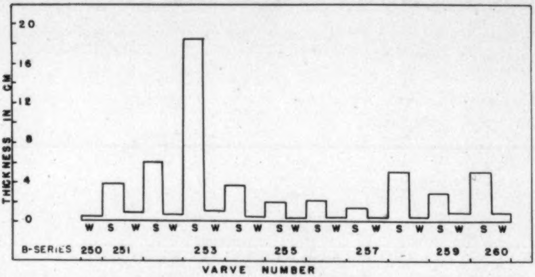

Fig. 2--Histogram of varve thickness

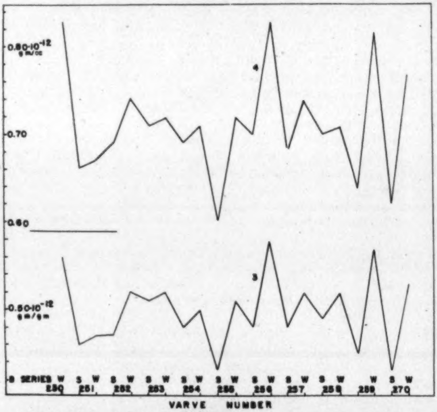

Fig. 3--Radium content; curve 3, grams per gram of dry varve; curve 4, grams per cubic centimeter of dry varve

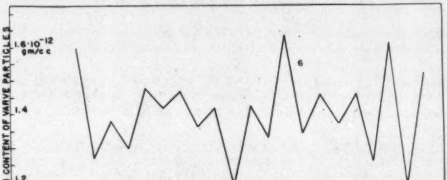

Fig. 4--Grams of radium per cubic centimeter of varve particles the summer and winter layers as indicated in curves 3, 4, and 6. The concentration of the radium is greater in the winter layers than in the adjacent summer layers, except in layer B221W as shown in curve 4. Curves 3 and 4 in Figure 3 and curve 6 in Figure 4 are for varves numbered B250 to B260 inclusive, that is, for the upper varves in Series B. The variations indicated in these curves are characteristic of all of the varves measured.

It was observed while determining the densities of the various samples that the relative decrease in the volume, when a moist sample was dried, varied considerably from sample to sample. Undoubtedly this was due to the water content of the different samples which varied from 0.40 to 0.12 gram of water per gram of dry material. The periodicity of the radium concentration seems to be best demonstrated when it is expressed in grams of radium per cubic centimeter of varve particles as shown in Figure 4. The upper solid curve was plotted for the winter layers of all of the varves sampled while the lower solid curve is for the summer layers. The broken line curve is the annual average radium content and was plotted from the data in column (6), Table 1. A particle size analysis of varve 252, using the standard pipette method, is tabulated in Table 2.

Table 2--Particle size distribution of varve 252

Equivalent spherical diameter	Varve 252S	Varve 252W
microns	pct	pct
> 22.1	1.25	4.47
22.1 - 11.0	0.00	0.72
11.0 - 5.5	6.67	0.97
5.5 - 2.76	34.38	0.57
2.76 - 1.38	34.67	5.76
1.38 - 1.13	5.07	10.03
1.13 - 0.87	4.45	15.06
0.87 - 0.69	3.08	9.80
0.69 >	10.42	52.62

In the summer layer approximately 70 pct of the particles lie between 1.38 and 5.5 microns in effective diameter while there are relatively few particles as large as 1.38 microns in the winter layer. This distribution of particle size for the Seattle varve is in agreement with that reported by RITTENHOUSE [1934] for varved clays from the northern Ontario region. The indication is that the higher radium content is associated with clay of smaller particle size. This is in agreement with our observations [SANDERMAN and UTTERBACK, 1941] concerning the radium concentration of marine sediments.

Summary and conclusions--The radium concentrations of the Seattle varves, when plotted against time, show a periodicity in concentration, the radium content of the winter layers being greater than that of the adjacent summer layers. Whatever assumptions one may make to explain the difference in concentration, this periodicity seems to be best represented when the radium content is expressed in grams of radium per cc of varve particles.

The radium content of the winter layers shows no gradual increase with time nor do the summer layers show a gradual decrease in radium content with time. Neither is the annual average radium content a constant as reported for the Hartford varves although the span of years covered in the two cases is approximately the same. In this respect the results offer no evidence of a disturbance in the radioactive equilibrium at the time the Seattle varves were deposited. The radium concentration of the summer and winter layers is not a function of their thickness.

The winter layers consist of a much greater percentage of small particles than occurs in the summer layers. A comparison of the radium concentrations with the specific surfaces (cm^2/gm) indicates that adsorption, to a considerable extent, is the reason for the differences in the radium content in the summer and winter layers. Due to the fact that there is no evidence of animal or plant life in the clays, it is unlikely that these differences can be attributed to biochemical extraction.

Mechanical analysis of these and other varves is being made with the expectation that these data will supply pertinent information concerning the mechanism of the deposition of the radioactive elements.

Acknowledgment--The authors express their appreciation of the assistance given by H. J. Kelly in a part of this work.

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POLYMORPHISM AND OROGENY

Brian Mason

Abstract--Two distinct causes are currently invoked to explain orogeny: thermal contraction of the Earth, and subcrustal convection currents. The purpose of this papar is to examine a third possibility: contraction as a result of a polymorphic change of the material within the Earth. In 1936 Bernal suggested a polymorphic change of $(Mg, Fe)_2SiO_4$ to explain the 20° discontinuity within the mantle; this suggestion is extended by proposing that the relative amounts of the polymorphic forms have varied during geological time. An increase in the amount of a denser polymorph would lead to a contraction of the Earth as a whole, resulting in crustal shortening and orogeny. Calculations show that the observed crustal shortening during geological time can be explained on this hypothesis.

Two major theories are current as to the source of the energy that produces crustal movements. Some geologists favor thermal contraction as the motivating factor, whereas others believe that forces engendered by subcrustal convection currents are responsible for orogeny. The theory of thermal contraction is the more venerable, but its position has been shaken since the discovery of radioactivity introduced uncertainly into the idea of an Earth that has been cooling down since its origin. As SLICHTER [1941] says ..... "present evidence on the thermal history of the Earth is inadequate to say whether the Earth is cooling down, is heating up, or is in a state of thermal equilibrium."

It appears to me that a possible source of the energy for crustal movements can be found in polymorphic changes of the material within the Earth. Polymorphic changes provide a mechanism for contraction or expansion, and for the conversion of thermal energy into mechanical energy. A polymorphic change involving contraction of the Earth's interior would provide the motivating force for orogenic movements within the crust.

The idea of polymorphism of the material of the mantle can be traced back to BERNAL [1936] in a brief comment to a geophysical discussion. He suggested that the second-order discontinuity within the mantle at a depth of about 400 km might be due to the formation of a high-pressure polymorph of olivine, pointing out that the analogous compound Mg_2GeO_4 exists in two modifications, one isomorphous with olivine and the other an isometric phase with the spinel structure and nine per cent higher density. Although it is not yet possible to test this hypothesis experimentally at the temperatures and pressures corresponding to conditions at that depth in the mantle, Bridgman's work on the properties of matter at high pressures has indicated that polymorphic changes are to be expected under such conditions. BIRCH [1952] has considered this hypothesis in rather more detail, and has suggested other polymorphic changes which might be expected within the mantle, such as the change of $MgSiO_3$ from a pyroxene to a corundum structure, and of SiO_2 to a rutile structure. He makes the point that, in order to explain the geophysical data on the mantle, high-pressure phases are required, and that oxide structures with the required elastic properties are known.

Thus the idea of polymorphic transitions within the mantle has support from both geophysical and physicochemical data. The present paper accepts this idea as a working hypothesis, and extends it by suggesting that the equilibrium between the polymorphs is not static but dynamic, that the proportions between the polymorphs have varied during geological time, and that contraction of the Earth's surface can be ascribed to an increase in the amount of the denser polymorph or polymorphs.

This is essentially what I had in mind when I wrote [MASON, 1952, p. 33] ". . . a polymorphic change of this sort within the mantle also provides a mechanism for periodic orogeny; an increase in the amount of the denser polymorph during geological time would result in contraction of the Earth as a whole, thus giving a plausible explanation for crustal shortening and orogeny. . ." It remains to attempt to put some quantitative meat on these rather bare qualitative bones.

JEFFREYS [1952, p. 308] makes the following statement regarding the amount of crustal shortening as a result of mountain-building " . . . . if we take the estimates given by isostasy, then as there have been three major epochs of mountain formation since the Cambrian and probably about five earlier ones, we are led to a total crustal shortening in the neighbourhood of 500 km . . . ." This amount of crustal shortening implies a reduction in radius of the earth of about 80 km. If the initial radius was R_a and the present radius is R_c, and V is the volume change, then

$$V = (4/3)\pi (R_a^3 - R_c^3)$$

This volume change has been brought about by the conversion of volume V_1 of the lighter polymorph (density D_1) into volume V_2 of the denser polymorph (density D_2). Now

$$V_1D_1 = V_2D_2$$

$$V_1 - V_2 = V_2D_2/D_1 - V_2$$

but $V_1 - V_2 = V$, and hence

$$(4/3)\pi (R_a^3 - R_c^3) = V_2(D_2/D_1 - 1)$$

If the initial distance from the center of the Earth of the boundary between denser and lighter polymorph was R_b and the present distance R_d, then

$$V_2 = (4/3)\pi (R_d^3 - R_b^3)$$

and hence

$$(R_a^3 - R_c^3) = (D_2/D_1 - 1)(R_d^3 - R_b^3)$$

Assuming that the 20° discontinuity is a boundary between a denser and a lighter polymorph, R_d is thus known, and R_b can be calculated, given a value for $(D_2/D_1 - 1)$. If the change is from an olivine structure for $(Mg, Fe)_2SiO_4$ to a spinel structure, $(D_2/D_1 - 1)$ would probably be about 1/8. The value of R_b thus determined is 5100 km, and the initial depth of the discontinuity would be 1350 km. Thus a crustal shortening of 500 km during geological time would imply a decrease in the depth of the discontinuity of about 1000 km, not an unreasonable amount. If $(D_2/D_1 - 1)$ were greater, that is, the difference in the densities of the two polymorphs were larger, as would be the case for the change of $MgSiO_3$ from a pyroxene to a corundum structure, the same amount of crustal shortening would imply a lesser change in the position of the discontinuity.

Of course, even if the hypothesis of crustal shortening through polymorphic changes in the mantle is correct, the actual situation is unlikely to be as simple as that outlined here. The situation may be complicated by more than one specific polymorphic change, if other compounds besides $(Mg, Fe)_2SiO_4$ are present in the mantle. Even in a mantle made up entirely of $(Mg, Fe)_2SiO_4$ the boundary between the two polymorphs would probably be a zone rather than a surface, the transition from one polymorph to the other depending on temperature, pressure, and the magnesium-iron ratio of the material, all of which can be expected to vary with depth. This would be in accordance with Birch's picture of the mantle, which he suggests is homogeneous below 900 km and inhomogeneous at lesser depths.

So far this discussion has been based on the idea of an increase in the amount of a denser polymorph or polymorphs and a resulting contraction of the Earth. It is conceivable, however, that the process need not always have gone in the same direction; perhaps at certain times a reversal might take place, with an increase in the amount of a lighter polymorph. This would result in expansion, producing a condition of tension in subcrustal and crustal layers that would cause large-scale rifting and uplift or depression of large segments of the crust. Such a process would provide a reasonable explanation for the formation of rift valleys and for the extrusion of the large masses of plateau basalts that characterize certain periods of Earth history.

The hypothesis also raises some interesting implications in connection with other geophysical phenomena. The depth of the proposed polymorphic change is also the region in which deep-focus earthquakes originate; perhaps deep-focus earthquakes are the expression of dynamic activity at these depths resulting from a change in the relative amounts of two or more polymorphs. The change from one polymorph to another involves the evolution or absorption of latent heat of transformation; what influence would this have on the thermal history of the Earth? These, and certainly other questions as well, remain to be explored.

I am indebted to Judson Mead for instructive discussions and suggestions in connection with this subject.

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THE USE OF V CONCEPT IN STRUCTURAL GEOLOGY

V. G. Gabriel and J. C. Dotson

Abstract--A generalized V concept is briefly defined for faults and formations which can be represented as idealized planes. Formulas are derived for mathematical, graphical, and net of vector curves solutions by using a generalized V pattern concept. The separation of idealized plane surfaces from curved ones is indicated. Finally, a few examples for the evaluation of the true dip and strike of a formation are given.

Introduction--With few exceptions, such as DAKE and BROWN [1925], the American geologists do not use widely the concept of V in detailed field studies of the structures under consideration. However, a clear understanding of the V concept and its use in structural studies should serve for better elucidation of the problems under consideration.

V concept--Dake and Brown emphasize the detailed studies of the patterns made by formations, the tops and bottoms of which can be taken as idealized planes, extending across relatively broad valleys made by streams or other agencies. Their conclusions can be briefly summarized in a rule of V's: The V will point in the direction of the true or apparent dip of a formation or a fault plane, except in a case where the true or apparent dip of the formation is numerically smaller than the gradient of the valley. In the latter case the V will point in the opposite direction. However, the concept of V, as expressed by Dake and Brown, is a rather narrow one. It can be extended in a generalized way not only for the study of formation patterns in extending across valleys but as well to the comparisons of formation patterns in areas of low and high relief.

Faults and formations assumed to be idealized planes--Fault planes and the top and bottom of certain sheet-like structures can be represented by idealized planes. Because of the spatial sim-

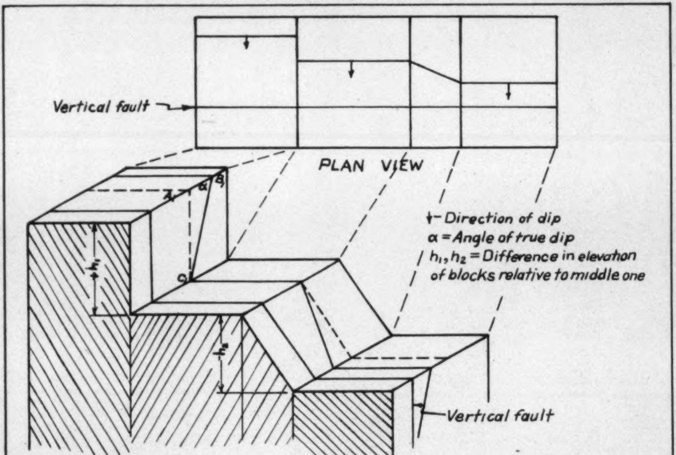

Vertical fault
PLAN VIEW
Direction of dip
α = Angle of true dip
h_1, h_2 = Difference in elevation of blocks relative to middle one
h_1
h_2
α
Vertical fault
OBLIQUE VIEW
Blocks of different altitude

Fig. 1--Traces of vertical and high-angle fault planes across blocks of different altitudes ilarity exhibited among structures having plane surfaces, investigation of a fault plane will illustrate the application of the V pattern in geology. A fault plane dipping 90° will have no V's in crossing valleys. Moreover, the trace of this fault on a map will be a straight line independent of the variations in altitude of the Earth's surface (see Fig. 1). The projection of traces of the fault planes having angles of dip assumed to be neither zero nor 90° will deviate from their respective fault traces in the middle block. The projection of traces of the dipping fault planes will deviate in a direction opposite to that of the direction of the true dip in the blocks located at higher altitudes. For the blocks located at the lower altitudes the projection of traces of the dipping planes will deviate toward the direction of the true dip as compared to that of the middle.

Derivation of formulas for blocks located at different altitudes--Assume that the differences in elevation of the higher and lower altitude blocks, relative to the middle one, are $+h_1$ feet and $-h_2$ feet respectively. From the right triangle $A_1B_1C_1$ located in a vertical plane $A_1B_1C_1$ (see Fig. 1), we have

$$A_1C_1 = h_1 = A_1B_1 \tan \alpha \ldots\ldots\ldots\ldots (1)$$

where

A_1B_1 = deviation in feet in a plan view from the fault trace of middle altitude block
$+h_1 = A_1C_1$ = difference in elevation of the two blocks
α = angle of the true dip

From (1) we obtain

$$h_1/A_1B_1 = \tan \alpha \ldots\ldots\ldots\ldots (2)$$

Similarly, for the blocks of various altitudes, the elevations of which are taken with respect to a certain block, we have for the plane dipping α degrees

$$h_1/A_1B_1 = \tan \alpha \ldots\ldots\ldots\ldots (3a)$$

$$h_2/A_2B_2 = \tan \alpha \ldots\ldots\ldots\ldots (3b)$$

$$\ldots\ldots\ldots$$

$$h_n/A_nB_n = \tan \alpha \ldots\ldots\ldots\ldots (3n)$$

or from (3) we have

$$h_1/A_1B_1 = h_2/A_2B_2 = \ldots = h_n/A_nB_n = \tan \alpha \ldots\ldots\ldots\ldots (4)$$

Eq. (4) shows that by taking the ratio of the deviation from the fault trace of the lower altitude block to the difference in altitude of the two blocks, the true dip can be evaluated. Moreover, if the ratios expressed by (4) are not equal, after the substitution of measured values for two or more blocks, then the fault plane or the formation plane is a curved surface.

The following set of equations can be derived from (4):

$$A_1B_1/A_2B_2 = h_1/h_2 \ldots\ldots\ldots\ldots (5a)$$

$$A_1B_1/A_3B_3 = h_1/h_3 \ldots\ldots\ldots\ldots (5b)$$

$$\ldots\ldots\ldots$$

$$A_1B_1/A_nB_n = h_1/h_n \ldots\ldots\ldots\ldots (5n)$$

Also from (5)

$$A_2B_2/A_3B_3 = h_2/h_3 \ldots\ldots\ldots\ldots (6a)$$

$$A_2B_2/A_xB_x = h_2/h_x \ldots\ldots\ldots\ldots (6b)$$

$$\ldots\ldots\ldots$$

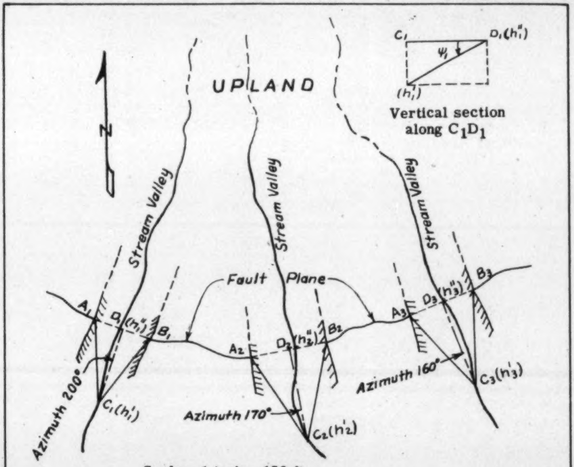
$$A_xB_x/A_yB_y = h_x/h_y \ldots\ldots\ldots\ldots (6n)$$

where x, y are any numbers.

If, upon the substitution of measured values of AB's and h's into (4), (5), and (6), the equality is not satisfied, it means that the planes under consideration are curved surfaces.

Idealized planes extending across valleys--As previously pointed out, the V's of the moderately dipping planes crossing the valleys will point, except in particular cases, toward the direction of the dip. However, in a territory possessing dendritic or irregular stream patterns, the evaluation of tangents from V patterns will yield the values of the apparent dips only, and not that of the true dip.

Mathematical solution--Assume a moderately south dipping fault plane crossing a few relatively broad stream valleys. Also assume that the true dip of the fault is much greater than the gradients of the streams of the area under consideration. Under these conditions, the fault plane extending across the stream valleys will exhibit well-developed V patterns with their apexes pointing south. Exception to this is the V patterns made by streams flowing along the directions which do not deviate more than a few degrees from the true strike of the fault plane. Designating the pertinent points of each stream V pattern (see Fig. 2) by letters $(A_1B_1C_1)$, $(A_2B_2C_2)$, $(A_3B_3C_3)$, etc., we will have a number of triangles such as $A_1B_1C_1$, $A_2B_2C_2$, $A_3B_3C_3$. Assume that the elevations of the apexes C_1, C_2, C_3, as they appear on the map, are h_1^1, h_2^1, h_3^1, respectively, and the elevations of the points D_1, D_2, D_3, located on the lines A_1B_1, A_2B_2, A_3B_3 are h_1^{11}, h_2^{11}, h_3^{11}, respectively. Therefore, the depths of the valleys in the areas covered by $A_1C_1B_1$, $A_2C_2B_2$, $A_3C_3B_3$ V patterns will be $(h_1^{11} - h_1^1)$, $(h_2^{11} - h_2^1)$, $(h_3^{11} - h_3^1)$, respectively. The angles of the apparent dips for $A_1C_1B_1$, $A_2C_2B_2$, $A_3C_3B_3$ V patterns will be ψ_1, ψ_2, ψ_3, respectively.



Scale: 1 inch = 150 ft

h_1^1, h_2^1, h_3^1 = elevations of the apexes of V's

h_1^{11}, h_2^{11}, h_3^{11} = elevations at D_1, D_2, D_3, respectively

C_1D_1, C_2D_2, C_3D_3 = length of V's

$_1$, $_2$, $_3$ = angles of apparent dip

Fig. 2--V's of stream valleys for a moderately dipping idealized plane

Mathematically it can be expressed as

$$(h_1^{11} - h_1^{1})/C_1D_1 = \tan \psi_1 \tag{7a}$$

$$(h_2^{11} - h_2^{1})/C_2D_2 = \tan \psi_2 \tag{7b}$$

$$(h_3^{11} - h_3^{1})/C_3D_3 = \tan \psi_3 \tag{7c}$$

where ψ_1, ψ_2, ψ_3 = angles of the apparent dips.

However, from a well-known formula [see GABRIEL and MILLER, 1952] we have

$$\tan \psi = \tan \alpha \cos \theta \tag{8}$$

where

ψ = angle of apparent dip
α = angle of true dip
θ = angle between the directions of true and apparent dips

From (7) and (8) we have

$$(h_1^{11} - h_1^{1})/C_1D_1 = \tan \psi_1 = \tan \alpha \cos \theta_1 \tag{9a}$$

$$(h_2^{11} - h_2^{1})/C_2D_2 = \tan \psi_2 = \tan \alpha \cos \theta_2 \tag{9b}$$

$$(h_3^{11} - h_3^{1})/C_3D_3 = \tan \psi_3 = \tan \alpha \cos \theta_3 \tag{9c}$$

By dividing (9a) by (9b) and (9c) we obtain

$$[(h_1^{11} - h_1^{1})/C_1D_1 \;/\; (h_2^{11} - h_2^{1})/C_2D_2] = \tan \psi_1/\tan \psi_2 = \cos \theta_1/\cos \theta_2 \tag{10a}$$

$$[(h_1^{11} - h_1^{1})/C_1D_1 \;/\; (h_3^{11} - h_3^{1})/C_3D_3] = \tan \psi_1/\tan \psi_3 = \cos \theta_1/\cos \theta_3 \tag{10b}$$

From (10) the true strike and true dip of the planes can be evaluated.

Field vector (graphical) solutions--GABRIEL and MILLER [1952] have discussed the application of the vector tangent and vector line of sine methods in graphical determination of the true dip and strike of a formation. Both methods can be conveniently applied in the V pattern concept by measuring the azimuths of lines C_1D_1, C_2D_2, and C_3D_3, and drawing from any selected point of the map three straight lines parallel respectively to lines C_1D_1, C_2D_2, and C_3D_3. By scaling off the magnitudes of the apparent tangents, if the vector tangent method is used, or the magnitudes of the valley depths adjusted for an identical length of V, if the vector line of sine method is used, the true strike and dip can be found by the intersection of two or more straight lines drawn from the end points of the measured azimuthal lines.

Diagrammatic method by net of vector tangent curves--From (8) for any plane, the true dip of which is equal to α degrees, the following set of equations can be written

$$\tan \psi_1 = \tan \alpha \cos \theta_1. \tag{11a}$$

$$\tan \psi_2 = \tan \alpha \cos \theta_2. \tag{11b}$$

. . . .

$$\tan \psi_n = \tan \alpha \cos \theta_n. \tag{11n}$$

where

$\psi_1, \psi_2, \ldots \psi_n$ = angles of apparent dips
α = angle of the true dip of the formation
$\theta_1, \theta_2, \ldots \theta_n$ = angles between the directions of the apparent dips and the true dip

By utilizing (11), the tangents of the apparent dips have been computed for the true dips equal to 10°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, and 80°, and for angles of θ from 0 to 90° at ten-degree

Table 1--Tangents and angles of true and apparent dips[a]

True dip α	Apparent dip ψ	Acute angle θ between directions of true and apparent dip									
		0°	10°	20°	30°	40°	45°	50°	60°	70°	80°
10°	Apparent ψ[b]	10°00′	9°51′	9°25′	8°41′	7°41′	7°06′	6°28′	5°02′	3°27′	1°45′
	Tan ψ[c]	0.1763	0.1736	0.1657	0.1527	0.1350	0.1247	0.1133	0.0882	0.0603	0.0306
20°	Apparent ψ	20°00′	19°43′	18°53′	17°30′	15°35′	14°26′	13°10′	10°19′	7°06′	3°37′
	Tan ψ	0.3640	0.3585	0.3421	0.3152	0.2788	0.2574	0.2340	0.1820	0.1245	0.0632
30°	Apparent ψ	30°00′	29°37′	28°29′	26°34′	23°52′	22°13′	20°22′	16°06′	11°10′	5°44′
	Tan ψ	0.5774	0.5686	0.5426	0.5000	0.4423	0.4083	0.3712	0.2887	0.1975	0.1003
40°	Apparent ψ	40°00′	39°34′	38°15′	36°00′	32°44′	30°41′	28°21′	22°46′	16°01′	8°18′
	Tan ψ	0.8391	0.8263	0.7885	0.7267	0.6428	0.5933	0.5394	0.4196	0.2870	0.1458
45°	Apparent ψ	45°00′	44°34′	43°13′	40°54′	37°27′	35°16′	32°44′	26°34′	18°53′	9°51′
	Tan ψ	1.0000	0.9848	0.9397	0.8660	0.7660	0.7071	0.6428	0.5000	0.3420	0.1737
50°	Apparent ψ	50°00′	49°34′	48°14′	45°55′	42°24′	40°07′	37°27′	30°47′	22°11′	11°42′
	Tan ψ	1.1918	1.1737	1.1199	1.0321	0.9129	0.8427	0.7661	0.5959	0.4076	0.2070
60°	Apparent ψ	60°00′	59°37′	58°26′	56°19′	53°00′	50°46′	48°04′	40°54′	30°39′	16°44′
	Tan ψ	1.7321	1.7058	1.6277	1.5000	1.3268	1.2248	1.1134	0.8660	0.5924	0.3009
70°	Apparent ψ	70°00′	69°43′	68°50′	67°12′	64°35′	62°46′	60°29′	53°57′	43°13′	25°31′
	Tan ψ	2.7475	2.7057.	2.5818	2.3793	2.1046	1.9428	1.7661	1.3738	0.9396	0.4772
80°	Apparent ψ	80°00′	79°51′	79°22′	78°29′	77°02′	76°00′	74°40′	70°34′	62°44′	44°34′
	Tan ψ	5.6713	5.5851	5.3293	4.9113	4.3442	4.0102	3.6455	2.8356	1.9396	0.9851

[a] Based on formula $\tan\psi = \tan\alpha\cos\theta$, where ψ = angle of apparent dip, α = angle of true dip, and θ = acute angle between directions of true and apparent dip.

[b] Angles correct to nearest minute.

[c] Tangents taken to fourth decimal place.

intervals (see Table 1). The computed tangents of Table 1 were plotted to scale along their respective azimuths, the directions of apparent dip, and the ends of these vector tangents were connected by smooth curves, so-called, vector tangent curves (see Fig. 3); each curve connects the tangent of the true dip and its corresponding tangents of apparent dips. On a sheet of tracing paper draw from a common center two or more lines corresponding in direction and magnitude to the tangent lines of apparent dip. By superposition of the tracing paper on the diagram of Figure 3 until two or more measured lines touch the curve representing a certain angle of true dip, the true dip and strike can be found.

Diagram (Fig. 3)--On the right side of the semicircle of unit radius, the vector tangent curves have been drawn for true dips ranging from zero to 45°. On the left side of the diagram, six concentric circles of radii equal to 1, 2, 3, 4, 5, 6 units have been drawn and the vector tangent curves plotted for the true dips ranging from 45 to 80°.

The plotting of tangent vectors of apparent dips is easily accomplished by accepting the fact that the ends of the tangent vectors for a particular true dip are located on a circle, the diameter of which is equal to the tangent of the true dip.

The acceptance of this fact is based on the following consideration: Assume a coordinate system x, y measured along the axis of true dip and the axis of true strike, and the center of the coordinate system located at point O (see Fig. 3).

For the end point of any tangent vector, the following equations hold:

$$X = \tan\psi_1 \cos\theta_1 \quad \text{(12a)}$$

$$Y = \tan\psi_1 \sin\theta_1 \quad \text{(12b)}$$

where

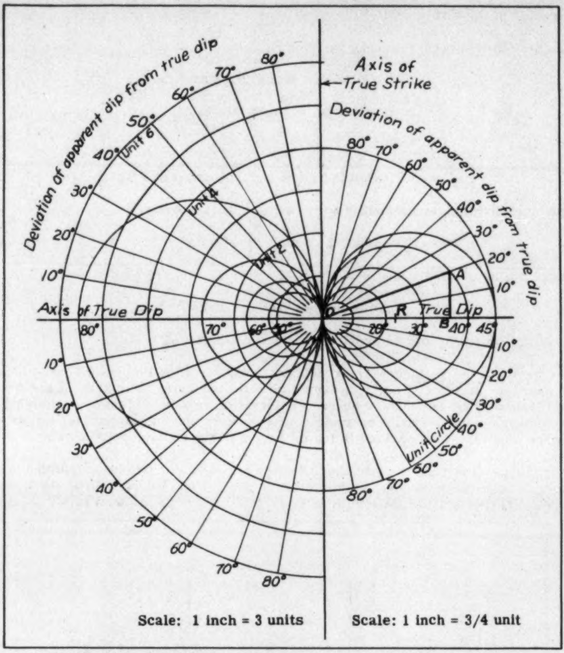

Axis of
True Strike
Deviation of apparent dip from true dip
Deviation of apparent dip from true dip
Unit 6
Unit 4
Unit 2
Unit Circle
Axis of True Dip
A
R
B
O
True Dip
10°
20°
30°
40°
45°
50°
60°
70°
80°
Scale: 1 inch = 3 units
Scale: 1 inch = 3/4 unit

Fig. 3--Net of vector tangent curves: on the right, a semicircle of radius equal to one; on the left, a set of concentric semicircles of radius ranging from one to six

X, Y = coordinates of the end points
X = OB
Y = AB
ψ_1 = angle of apparent dip
θ_1 = acute angle between directions of true and apparent dips

From (11), by substitution of the value of tan ψ into (12), we have

$$X = \tan\alpha \cos^2\theta_1 \quad \text{(13a)}$$

$$Y = \tan\alpha \cos\theta_1 \sin\theta_1 \quad \text{(13b)}$$

Assume that the end points of all the tangent vectors for a particular true dip are located on the curve of a circle, the center of which is located on the axis of true dip. Assume that the center of this circle is located at R. For the new coordinate center at point R, the following equation can be set for the end points of the tangent vectors:

$$BR = OB - OR = X - r \quad \text{(14a)}$$

$$AB = Y \quad \text{(14b)}$$

where r = radius of the circle = OR.

By substitution from (13) into (14), we have

$$BR = \tan \alpha \cos^2 \theta_1 - r \qquad (15a)$$

$$AB = \tan \alpha \cos \theta_1 \sin \theta_1 \qquad (15b)$$

From (15)

$$r^2 = \overline{BR}^2 + \overline{AB}^2 = (\tan \alpha \cos^2 \theta_1 - r)^2 + (\tan \alpha \cos \theta_1 \sin \theta_1)^2 \qquad (16)$$

By squaring, dividing, and transposing terms of (16), we obtain

$$\tan^2 \alpha \cos^2 \theta_1 (\cos^2 \theta_1 + \sin^2 \theta_1) - 2r \tan \alpha \cos^2 \theta_1 = 0 \qquad (17)$$

From (17) we have

$$\tan \alpha \cos^2 \theta_1 (\tan \alpha - 2r) = 0 \qquad (18)$$

This solution gives $\tan \alpha = 2r$ provided $\tan \alpha \neq \infty$ or $\alpha \neq 90°$.

V patterns of curved surfaces--If for measured values of the lengths (CD) and heights (h) of V patterns (see Fig. 2), (7), (9), and (10) cannot be satisfied in the evaluation of the true dip of a plane, then it follows that the surface under consideration is a curved one. In studying the V's of the curved surfaces, each V should be evaluated separately and the angle of dip so obtained should be taken as the true dip of the surface in the direction of the V under consideration.

First problem--Given Block I and Block II (see Fig. 4), the altitudes of which are h_1 and h_2, respectively. A fault plane dipping south intersects Block I and Block II along the fault trace lines A_1B_1 and C_2D_2, respectively. Assume h_1 is equal to 50 ft and h_2 is equal to 100 ft. Find the true dip of the fault. Solution: Let us draw a line K_2A_2, the continuation of the line A_1B_1, on Block II. The line A_2K_2 would be the trace of the fault plane if Blocks I and II were of the same altitude, that is, h_1 feet. From a triangle $A_3C_3N_3$ located in the side view projection, we have

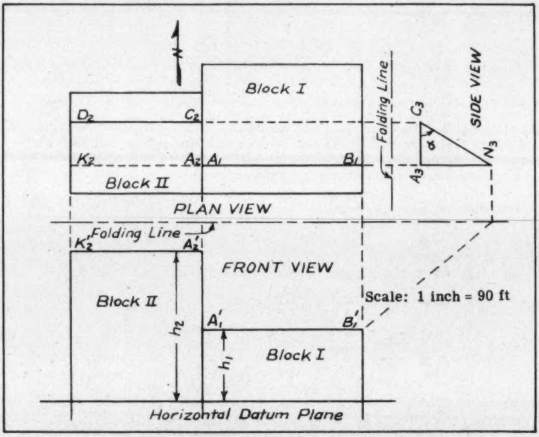


Fig. 4--Plan and auxiliary view projections of two blocks of different altitudes for the solution of the first problem

$$A_3N_3 = A_3C_3 \tan \alpha \qquad (19)$$

However

$$A_3N_3 = h_2 - h_1 = (100 - 50) \text{ ft} = 50 \text{ ft} \qquad (20a)$$

$$A_3C_3 = A_2C_2 = 30 \text{ ft (by scaling off from the map)} \qquad (20b)$$

By substituting into (19) the magnitudes of A_3N_3 and A_3C_3 from (20), we have

$$50 \text{ ft} = 30 \text{ ft} \times \tan \alpha \qquad (21)$$

or from (21)

$$50/30 = 5/3 = 1.6667 = \tan \alpha \qquad (22)$$

or $\alpha = 59° \, 02'$ approximately.

Second problem--Given three V stream patterns of a formation or a fault plane designated by the triangles $A_1B_1C_1$, $A_2B_2C_2$, $A_3B_3C_3$ (see Fig. 2), the azimuths of their central lines C_1D_1, C_2D_2, C_3D_3 are 200, 170, and 160°, respectively. The elevations of the points C_1, C_2, C_3 are h_1, h_2, h_3, respectively. The elevations of the points D_1, D_2, D_3 are h_1'', h_2'', h_3'', respectively. Find the true strike and dip of the formation by using diagrammatic, that is, the vector tangent curve method. Solution: Assume that from the topographical contours the differences in elevations $(h_1'' - h_1)$, $(h_2'' - h_2)$, and $(h_3'' - h_3)$ have been found to be equal to 50, 40, and 30 ft, respectively. By scaling from the map (Fig. 2), the lengths C_1D_1, C_2D_2, C_3D_3 were found to be equal to 92, 108, and 104 ft, respectively. Therefore, from (7)

$$(h_1'' - h_1)/C_1D_1 = 50 \text{ ft}/92 \text{ ft} = 0.5435 = \tan \psi_1 \qquad (23a)$$

$$(h_2'' - h_2)/C_2D_2 = 40 \text{ ft}/108 \text{ ft} = 0.3704 = \tan \psi_2 \qquad (23b)$$

$$(h_3'' - h_3)/C_3D_3 = 30 \text{ ft}/104 \text{ ft} = 0.2885 = \tan \psi_3 \qquad (23c)$$

where ψ_1, ψ_2, ψ_3 = angles of the apparent dips.

Let us take a sheet of transparent paper and draw from a common center three straight lines making the angles β_1 and β_2 to their central line, where

$$\beta_1 = 200° - 170° = 30° \qquad (24a)$$

$$\beta_2 = 170° - 160° = 10° \qquad (24b)$$

By scaling the values of $\tan \psi_1$, $\tan \psi_2$, and $\tan \psi_3$ along their respective straight lines and placing the transparent sheet over the center of the diagram (see Fig. 3), a curve simultaneously satisfying the three tangent vectors is found. This curve corresponds to the true dip of 30°. Because the azimuth line of 200° is located 20° east of the true dip of the plane in question, the azimuth of the direction of the true dip is 220° and the azimuth of the true strike is (220-90) or 130°.

Summary and conclusions--Amplification of the V concept as used by Dake and Brown will greatly expedite the evaluation of true dips and strikes of idealized planes as illustrated herein. Data obtained from ordinary field surveying methods or from topographic-geologic maps are readily incorporated in the solutions by these methods. A broader V concept makes possible the analysis of formation patterns wherever a relief differential exists.

The net of vector tangent curves may be constructed rapidly and without difficulty because for a given true dip the end points of the vector tangents form a circle the diameter of which is equal to the tangent of the true dip. The graphic solution that is used in conjunction with the net of vector tangent curves requires the construction of only two lines; a third line may be used as a check. If the end points of three vector tangents that originate from a common point do not lie on a circle which passes through the point of origin, a curved or irregular surface is indicated. Increasing the scale and closer spacing of the vector curves (let us say, to two-degree intervals) on the net diagram will increase considerably the accuracy of diagrammatic interpretation.

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REPORT OF THE COMMITTEE ON THE DYNAMICS OF STREAMS, 1951-1953

J. W. Johnson, Chairman

1953	1954	1955
Paul Bauman	Francis Escoffier	D. C. Bondurant
Whitney M. Borland	H. V. Peterson	E. F. Brater
Carl F. Izzard	Ralph W. Powell	Frank B. Campbell

The report of the Committee consists of a survey of current activities compiled by Committee members in correspondence with known workers in the field of stream dynamics.

Whitney M. Borland (U. S. Bureau of Reclamation, Denver, Colorado)--The following is a compilation of work being carried out by the Hydrology Branch and the Hydraulic Laboratory, Design and Construction Division, United States Bureau of Reclamation. Some of the work is being done on a cooperative basis with other agencies.

Bed-load studies--In the flume or turbulent sill on the Middle Loup River near Dunning, Nebr., bed-load studies based on data obtained by the U. S. Geological Survey are being continued by the Hydrology Branch and the U. S. Geological Survey. Studies and reports made on the results of the field data for the period ending in December, 1951, were included in the Report of the Committee on Dynamics of Streams in the *Transactions* of February, 1952. Present studies include analysis of data at various sections above and below the flume and at the flume in regard to vertical distribution of sediment, variation of size distribution with depth, temperature effect on concentration, as well as comparison of total load measured and total load computed by various bed-load equations.

A detailed study to determine the total sediment load of the Niobrara River near Cody, Nebr., was initiated by the Hydrology Branch; the Area Office, Ainsworth, Nebr.; and the U. S. Geological Survey in June, 1951. At this location the Niobrara River is confined for a short distance in a narrow slot section where sufficient turbulence is created to throw practically all the sediment being transported into suspension, thereby enabling the measurement of total load [SERR, 1950]. In addition to the determination of the total sediment transport of the Niobrara River at this point to be used in conjunction with proposed Bureau of Reclamation projects in the area, the data are to be used to aid in the evaluation of the measured total load as compared with that computed by various bed-load equations, particularly the Einstein bed-load function. Studies made at the Dunning Flume, although conclusive, did not afford the opportunity to evaluate the total load throughout a range in water discharge. Sampling is being carried out at the constricted section at the normal gaging station a short distance upstream and at ten cross-section ranges throughout an approximate two-mile reach of the river downstream.

To date a complete set of field data have been obtained at discharges varying from 200 to 800 cfs. When measurements have been obtained at a discharge of 1000 cfs or over and less than 200 cfs, the field data will be considered complete. A flood of 5000 cfs was experienced during July of 1952, but no measurements in the study sections other than gage height readings were possible because of the short duration of the flood.

On the Middle Rio Grande, extensive sediment studies are being carried out by the U. S. Bureau of Reclamation Area Planning Office at Albuquerque, N. Mex., to determine the total sediment load carried by the Middle Rio Grande at various points for both present and future conditions. During the spring runoff period of 1952, measurements at 13 sections in an approximate three-mile reach of the river near Bernalillo, N. Mex., were carried out with the cooperation of the U. S. Geological Survey. The measurements included suspended sediment sampling (both depth-integrated and point-integrated), water discharge measurements, bed-material sampling, cross-section measurements, and slope determinations. Considerable analysis has been carried out so far with the immediate goal being the establishment of a total sediment load rating curve. In addition to determining the total load it will be necessary, in connection with future controlled channel degradation, to determine the transportability of the various sizes of material found in the bed. Computations of unmeasured load to date have utilized the Einstein bed-load function and the vertical distribution type analysis [SCHROEDER and RAITT, 1952]. Results have not been entirely satisfactory since the unmeasured portion shows considerable variation for a given discharge although the total transport may be about the same. Present studies are aimed at ironing out these differences by more thorough investigation of the velocity and sediment distribution and effective stream gradient.

Total suspended sediment load from vertical transport distribution--In connection with the determination of the total sediment transport of the Snake River near Burge, Nebr., for use in computations of sediment inflow to the proposed Merritt Reservoir, a method of computing the total suspended-load transport from point sampling data was devised [SCHROEDER and RAITT, 1952]. Obtainment of the necessary field data was carried out on a cooperative basis by the Hydrology Branch, and Area Office at Ainsworth, Nebr., of the U. S. Bureau of Reclamation and the U. S. Geological Survey. Analysis of the data was performed by the Hydrology Branch and the Ainsworth Office. The method employed in the analysis gave satisfactory results and it has been applied to other streams with similarly good results. Present procedures used in computing the sediment moved by a stream assume that the concentration obtained by a depth-integrating sampler is applicable for the entire depth of the stream (not considering corrections made for bed load). This assumption is, of course, incorrect. The degree of incorrectness is dependent upon the depth of the stream and the nature of the sediment load being carried. Present methods of determining the unmeasured portion of the sediment load by a bed-load equation requires obtainment of considerable field data. The vertical distribution method presents a means of determining the total suspended load with a minimum amount of field work and office analysis. Basically, the method used is an elaboration of the vertical sediment distribution presented by VANONI [1946]. The suspended sediment distribution equation is

$$C/Ca = [(d - y)/y]^{z} [a/(d - a)]^{z}$$

This equation has been modified to

$$CV = K [(d - y)/y]^{z'}$$

The revised equation includes the addition of velocity and substitution of K for $Ca[a/(d - a)]^{z}$.

With this equation and a plotting of (d - y)/y versus CV, it is possible to determine the unmeasured suspended load. The procedure, in effect, involves the extension of the suspended transport curve (CV versus depth) beyond the sampling limit. This permits the development of a relationship between the portion above (measured) and the portion below (unmeasured) the sampling limit.

Not evaluated in the method is the contact load. However, on the Niobrara River near Cody, Nebr., where the natural flume enables the measurement of total load, the vertical distribution analysis checks the measured total load within six percent. This six percent is assumed to represent the contact load. The conclusion, therefore, is that even in the stream in the sand hills the actual contact load is relatively small.

In this vertical distribution analysis it becomes clear that the field data and laboratory analysis must be as accurate as possible. Other applications of this type of analysis include the determination of the quantities of sand to be handled in diversions, a determination of the transport of various sizes of materials, and the development of a total suspended sediment-rating curve.

Analysis of flow-duration sediment-rating curve method of computing sediment yield--The present standard method utilized by the Bureau of Reclamation in determining the mean annual suspended-sediment transport of a stream is the flow-duration, sediment-rating curve type of analysis [MILLER, 1951]. This method requires a reasonably long record of sediment sampling and a sufficiently long discharge record to derive a representative long-time flow-duration curve. The discharges for various percentages of time from the flow-duration curve are combined with the sediment load in tons per day for the various discharges on the sediment-rating curve. This combination of discharge and sediment enables the determination of a mean daily sediment load for use in long-time prediction of sediment inflow to a reservoir. Some of the pitfalls and methods of approach to this type of analysis are pointed out in the referenced report by utilizing sediment and discharge records available for the San Juan River. Of particular note is the magnitude of the error introduced when using sediment records obtained during a dry year or period and the apparent definition by the data of sediment-rating curves for various seasons of the year and sources of stream flow. It was evident in the analysis made that a few years of sediment sampling during normal or near normal years was adequate to define the long-time sediment yield of the stream if no unusual conditions such as upstream developments interfered with the water-sediment relationship.

Stable channels--A progress report on stable channels has been published by the Hydraulic Laboratory [LANE, 1952] in which improved methods of design for stable channels in coarse granular material is presented. The method is based on the theory that certain sizes of coarse granular material will withstand limiting tractive forces. The study includes the effect of the angle of repose of the material on the channel side slopes on the tractive force that is allowable. These studies are mainly based on data from straight uniform canals in the San Luis Valley, Colorado. Several graphs and tables are presented to assist in the design of stable channels. From the data obtained from the San Luis Valley canals a correlation between size of bed material and the Manning roughness value n has been derived.

The results of the studies made in the San Luis Valley indicated that to determine a critical size in mixtures of coarse materials that will withstand certain tractive forces is very difficult from field data. This has led to a proposed laboratory study in an eight-foot wide by two-foot depth flume in which known mixtures of material will be placed. After running at known tractive forces the amounts of various sizes of materials removed will be determined. The tractive force flume will also be used to determine the distribution of tractive force on various degrees of curvature in canal sections. An interim study is being conducted in the flume in which the stability of wind-blown dune sand resistance to scour is being studied in connection with a proposed Bureau project in the sand hills region of Nebraska.

A paper on stable channels will be presented by E. W. Lane and E. J. Carlson at the meeting of the International Association of Hydraulic Research at Minneapolis, Minn., in September, 1953.

Turbulence tank--A study has been completed which evaluates the effect of temperature and turbulence on concentrations of various sizes of glass beads. Also the effect of turbulence on settling rate and concentration of flat particles was studied and the effect of seepage in through the bottom and out through the bottom of the tank on sediment concentration. A report is being prepared by personnel of Colorado A. and M. College, Fort Collins, Colorado, to whom the work was contracted.

Diversion structures--Several model studies have been completed in which sediment control arrangements were studied at the headworks and sluiceways of diversion structures. Guide walls which forced the flow to curve as it entered the headworks and sluiceway causing the coarse-bed sediments to go inside of the curve and out the sluiceway were utilized. The vortex tube with a horizontal actuating vane and a short tunnel leading to the sluiceway were tested and proved to work satisfactorily. The use of guide walls was analyzed separately and in conjunction with the vortex tube and short tunnel. The short tunnel in which the horizontal fake floor separates top and bottom water with bottom water going out the sluiceway and top water to the canal gave the largest ratio of sluiceway concentration against headworks concentration. A paper by H. M. Martin and E. J. Carlson entitled Model Studies of Sediment Control Structures on Diversion Dams will be presented at the meeting of the International Association of Hydraulic Research at Minneapolis, Minn., in September, 1953.

Desilting works--A preliminary compilation, including desilting works in many foreign countries as well as the United States, has been made by E. W. Lane giving descriptions and discussing the good and bad features of each. This compilation has been given only limited distribution within the Bureau and is the first step in the study of economic effective desilting works.

Francis Escoffier (Mobile District, Corps of Engineers, Mobile, Ala.)--The Mobile District conducted field and laboratory studies from November 9, 1944, through January 9, 1946, to establish the upstream limit of salt-water intrusion in the Mobile River and its tributaries. The results of these studies are summarized in House Document 773, 80th Congress, 2nd Session. A program was initiated in September, 1952, to supplement the earlier studies. It is proposed to investigate the action of the salt-water wedge throughout the tidal cycle at extreme low flow and during strong wind tides. An attempt will be made to develop a method of predicting the movement of the salt-water wedge under these conditions. It is estimated that this study will last about three years.

Basic research on the mechanics of flow through open-channel constrictions is being conducted at Georgia Institute of Technology under the sponsorship of the U. S. Geological Survey. The purpose of the initial investigation was to define the coefficients necessary to computing peak flood discharges through bridge openings from water-surface elevations defined by high-water marks and a survey of the characteristics of the channel. The first phase of the project which dealt with flow through vertical-faced constrictions was summarized in a paper given by Kindsvater and Carter at the convention of the American Society of Civil Engineers in March, 1952. The second phase of the project dealt with constrictions whose geometry was similar to that of bridge abutments commonly found in this country. This work has been completed and will be published as a U. S. Geological Survey Circular. Additional studies are now being conducted to determine the amount of backwater caused by open-channel constrictions. Future studies dealing with flow through multiple-bridge openings are planned.

Carl F. Izzard (Bureau of Public Roads, Washington, D. C.)--The Iowa Institute of Hydraulic Research is continuing research on three sedimentation projects under the joint sponsorship of the Iowa State Highway Commission and the Bureau of Public Roads. These projects include scour around bridge piers, transportation of sediment in a closed conduit with free water surface and under pressure, and trapping of sediment in a rectangular trap on a conduit. A progress report on the bridge scour research has been published in the Proceedings of the Highway Research Board in 1952. The instrument for recording scour described in that report is being perfected for installation on an existing bridge pier in the Skunk River in Iowa.

A preliminary report on sediment transportation in a pipe line will shortly be published in the Proceedings of the Fifth Hydraulic Conference held at the University of Iowa in June, 1952. No reports have been published on the sediment trapping experiments.

J. W. Johnson (University of California, Berkeley, Calif.)--A laboratory study of the velocity distribution in channel bends has been completed recently at the University of California. This study was concerned with a description of the crosswise velocity distribution observed in relatively wide shallow channel bends at points beyond the influence of entry conditions. The existence of relatively high velocities near the outside bank of such channel bends, heretofore accepted without adequate explanation, is shown to require the existence of a boundary layer along the bed in addition to the helical flow first described by James Thomson in 1876. A quantitative treatment of the interaction between the secondary currents and the main flow provides a theory from which the crosswise gradient of the tangential velocity can be predicted. Since secondary currents and the lateral distribution of velocities are both associated with river meandering, it is hoped that a better understanding of these phenomena may eventually result in a more complete theory of river meandering.

Another study completed at the University of California pertained to open channel flow of water-air mixtures in tranquil flow. The problem was analyzed in analogy with that of sediment transport. The vertical distribution of air in a turbulent mass was found to follow the laws of suspension. The average flow velocity and flow depth was predicted theoretically as a function of the air concentration and was checked by measurements in model channels.

The following phases of the problem on sediment transportation in alluvial rivers have been studied:

The segregation of bed material--When the river bed consists of material with a large spread of grain sizes, the bed material has a strong tendency to segregate [EINSTEIN and CHIEN, 1953] non-moving particles, if any exist in the bed, and slow-moving particles tend to accumulate in surface layers of the bed during the transport. This segregation of bed material has a strong effect on the transport rate of various sediment sizes, especially on that of the fine particles. An empirical parameter was established which indicates the degree of bed material segregation, and its effect on the transport rate. It was also found that when the local flow around the bed particles becomes laminar, the lifting coefficient of these particles is no longer a constant, but changes inversely proportional to the Reynolds number of the grain. With these two generalizations, the applicability of the Einstein bed-load function can be extended down to a grain size of ten microns.

Well-graded material deposits at high rates in the form of alternate coarse and fine layers, even if the flow conditions remain unchanged. This should prove very significant to geologists, who are interested in the history of river deposits.

The behavior of wash load--The transport rate or wash-load was found to follow the bed-load function if the instantaneous bed composition is known [EINSTEIN and CHIEN, in press]. Only the bed composition as determined from the instantaneous conditions of the channel has no lasting significance so far as the wash load is concerned. There is no way of predicting what the bed composition with respect to the wash load will be, as it depends mainly on the various factors in the upstream watershed which determine the availability of this sediment. It is due to this large variability of the amount of wash-load material in the bed that there exists no unique relationship between the transport rate of wash load and the flow.

The theory of suspension--Both flume studies and river measurements indicate that the existing suspended-load theory fails to describe the actual conditions in that the theoretical exponent Z is larger than the exponent Z_1 which fits experimental data [EINSTEIN and CHIEN, 1952]. The distribution of the suspended load is generally more uniform than that indicated by the theory. A preliminary study of this problem indicates that the conventional suspended-load theory can be revised on the following aspects: (1) The difference in sediment concentrations at a vertical distance ℓ apart is given by $\ell dc_y/dy$ only for fine particles. For coarse particles, the higher derivative terms of the concentration c_y with respect to the vertical distance y have to be included. (2) It is not sufficient to describe the scale and intensity of the turbulence at any elevation by the respective statistical average value only. Deviations from the averages also must be introduced. (3) The improved suspended-load theory appears to yield results comparable to those given by river measurements.

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REPORT OF COMMITTEE ON THE PHYSICS OF SOIL MOISTURE, 1952-1953

G. B. Bodman, Chairman

J. E. Christiansen J. R. McHenry J. S. Robins
R. M. Hagan R. D. Miller C. M. Woodruff

The report of the Committee is in two parts. The part below consists of a summary of research in progress on the physics of soil moisture. The Committee has also sponsored a paper and discussion on, Does Transpiration Decrease as the Soil Moisture Decreases?, a subject which has given rise to much controversial discussion in recent years. The Committee is indebted to F. J. Veihmeyer, President, Section of Hydrology, AGU, and A. H. Hendrickson, two pioneer investigators in this field, for submitting their point of view in the paper for subsequent discussion. This will be submitted soon for publication.

The report of the research in progress and the geographical distribution of workers on the physics of soil moisture in agricultural colleges and departments in the United States, Alaska, Hawaii and Puerto Rico is as follows.

Requests for information concerning research problems on the physics of soil moisture, and of the investigators currently engaged in the research, were sent to all land-grant colleges of agriculture and experiment stations, and to research organizations of the United States Department of Agriculture known to be interested in this area of investigation. The requests emphasized that information was being sought concerning research on the physics of soil moisture. It is realized that, inadvertently, some organizations may not have received the request and that, owing to its size, this may be particularly true of some branches of the U. S. Department of Agriculture (USDA). Omission of their names from the report is unintentional and it is hoped that they will communicate their research activities in the physics of soil moisture to the Committee for use in subsequent reports.

Response to requests was good and replies were received from over 95 pct of those to whom they were sent. The information obtained may be considered fairly representative of the kinds of current research on the physics of soil moisture among the large group of investigators questioned. Different interpretations were placed upon the term: physics of soil moisture. Titles used by the research workers themselves in describing apparently identical work in progress at different places differed, in some instances, more than did the titles of experiments with different objectives.

An inclusive rather than a restricted interpretation of the term was maintained during analysis of the data. Owing to the important role of soil water in all soil physical phenomena, and its inseparability from them, the inclusion of certain more general soil physics researches is unavoidable. Of necessity a certain amount of interpretation of submitted titles was undertaken and the many problems under investigation which were reported to the Committee were divided into a number of groups. The major categories of subdivision are: (1) Problems of static equilibrium; (2) Problems of kinetic equilibrium (steady state); and (3) Problems of non-equilibrium and non-steady state. These, in turn, were subdivided to give a total of 24 classes, all of which are listed in Table 1. The Committee hopes that any errors resulting from this treatment will be of only minor significance.

Table 1--Research in progress on the physics of soil moisture[a]

Problem	Class	Geographic areas and workers
Static Equilibrium	Measurement (other than tension methods under structure, below)	Calif 8, 9, 10, 13, 23, 24, 25, 26; Fla 1, 2; Ill 1; Miss 1; Pa 3, 4; Wis 1, 4; Wyo 1 Neutron methods: Ia 11; NJ 2, 3; NC 4; Utah 3, 4
	Thermodynamics and energy relations	Calif 1, 5, 9, 10, 11, 14; Ind 3; Utah 3, 8; Wash 1, 2

(Continued)

Table 1--Research in progress on the physics of soil moisture[a] (continued)

Problem	Class	Geographic areas and workers
Static equilibrium (concluded)	Swelling, shrinkage, osmotic pressure, and ionic influences	Calif 1, 4; Ind 3; NY 2, 3, 4, 5; NC 2, 3; PR 2, 8, 10, 11
	Mechanical properties	Ala 2, 5; Calif 18; Me 1
	Mechanical stresses	Ala 2, 6; Calif 2, 6
	Structure, pore size distribution, moisture characteristics, and hysteresis	Ala 2, 6; Calif 4; Conn 1, 3; Fla 2, Md 1, 2, 3; Mich 1, 2; NC 2, 3; NJ 1; PR 8, 10, 11; SD 2, 3, 4; Tex 1, 5; Wis 2, 3, 4; Wyo 1
	Amendments and conditioners affecting structure	Ala 2, 6; Calif 2, 8; Conn 1, 2, 3; Ia 2, 4, 13; Kans 1, 2; NJ 1; Pa 1
Kinetic equilibrium (steady state)	Permeability (soil approximately saturated with water), hydraulic conductivity	Alaska 1; Calif 3, 5, 19, 21; Ida 1, 2, 3; Ill 1; Ia 2, 4; La 1; Mass 1; NC 2, 3; NY 1; Ohio 3; SD 2, 3, 4; Tex 1; Utah 9; Va 1
	Permeability (soil unsaturated with water)	Calif 18, 20, 22; Ia 12; Ill 1; Utah 1, 3; Wash 2, 5, 7, 8
	Permeability of anisotropic columns and soil profiles	Calif 5, 11; Colo 2, 4, 5, 8; Conn 3; Ia 4, 5; Pa 1
	Water flow and temperature influences	Ia 6, 15; Utah 1, 3
	Water-vapor movement	NC 2, 3; Utah 1, 3
	Crop response under conditions of controlled tension, water-table position, etc.	Calif 8, 9, 10, 13, 19; Colo 1, 3; Mont 2, 3; PR 2, 8, 9, 10, 11; RI 1; Wis 4
Non-equilibrium and non-steady state	Field capacity, retention	Alaska 1; Fla 2; Ga 1; Mo 2; Nebr 1, 6, 10; Pa 1, 2; PR 3, 4, 5, 6, 11; Wash 8; Wis 3, 4
	Irrigation	Calif 8, 9, 10, 27; Colo 7; Ida 5; Mass 1; Nebr 2, 4, 8; SD 1; Utah 6; Wash 2, 6, 8
	Infiltration, including effect of conditioners	Ariz 1, 2, 3, 4; Calif 2, 3, 21, 23, 24, 25, 26; Colo 6; Fla 2; TH 2; Ida 4; Ind 2, 4, 5, 6; Mass 1; Mich 1, 3; NM 3; Ohio 1, 2, 3; PR 1, 5; Wash 2, 3, 4
	Infiltration and soil management	Calif 7, 8, 10, 12, 13; Ida 1, 2, 3; Kans 3; Me 1; Nebr 1, 3, 6, 10; Ohio 1, 2, 3; Ore 1; PR 5, 6; Tenn 1; Tex 1, 5
	Drainage, water table, capillary fringe	Ariz 1, 2; Calif 11, 16; Colo 7; Fla 2, 3; Ind 1, 2; Ia 1, 2, 3, 4, 8, 9, 14; Nebr 4, 7, 11; PR 5, 6; Tex 3, 4; Utah 7, 8; Va 2
	Temperature influences	Calif 9; Tex 1, 5
	Water vapor, evaporation	Calif 10, 13; Fla 2; Mont 1, 2; Tex 5
	Evapo-transpiration	Ala 1, 3, 4, 6; Ariz 1, 2; Calif 8, 9, 10, 13, 23, 24, 25, 26; Ia 16; Ida 4; Mich 5; Miss 1; Mo 1, 2; NC 1; Pa 3, 4; SC 1; Tenn 1; Tex 3, 4; Utah 5; Wash 2, 7, 8

(continued)

Table 1--Research in progress on the physics of soil moisture[a] (concluded)

Problem	Class	Geographic areas and workers
Non-equilibrium and non-steady state (concluded)	Crop performance	Calif 15, 17; TH 1; Nebr 5, 8, 9; NM 1, 2; Pa 2; Utah 2, 3, 6; Wyo 1
	Wetting and Wettability	Fla 2, 4; Kans 1, 2
	Water movement, general (for example, movement in vicinity of roots)	Calif 8, 15, 18; TH 2; Ia 2, 7, 10; Mich 1, 4

[a] Abbreviations relate to states and territories; the numbers to individuals. See Table 2 for key. Table 2 also shows organizations and geographic locations. In many instances, workers in a given region cooperate closely on individual problems.

The groupings decided upon are not intended to be exclusive of others and different arrangements will suggest themselves to the reader. It is believed, however, that the categories used will be helpful in enabling investigators engaged in related research to make contact either by correspondence or through the literature. It would be advantageous if future summaries of this kind could be made world-wide.

Table 2--Geographic distribution of workers currently engaged in research on the physics of soil moisture

Location	Organization[a]	Workers (key to numbers of Table 1)
Alabama	USDA BPISAE Tillage Machinery Laboratory, Auburn	1. A.W. Cooper 2. V.C. Jamison 3. Lloyd Johnson 4. R.W. Pearson 5. C.A. Reaves 6. H.A. Weaver
Alaska	University of Alaska, Palmer	1. N. Michaelson
Arizona	USDA FS Southwestern Forest and Range Experiment Station, Tucson	1. H.C. Fletcher 2. L.R. Rich
	SCS at Univ. Arizona, Tucson	3. J.E. Fletcher 4. K. Harris
California	University of California, Dept. of Soils, Berkeley	1. I. Barshad 2. G.B. Bodman 3. R.B. Campbell 4. N. Collis-George 5. P.R. Day 6. D.B. Peters
	Dept. of Irrigation, Davis	7. R.H. Burgy 8. L.D. Doneen 9. R.M. Hagan 10. D.W. Henderson 11. J.N. Luthin 12. V.H. Scott 13. F.J. Veihmeyer
	Dept. of Soils, Davis	14. L.E. Davis
	Dept. of Irrigation and Soils, Los Angeles 24	15. M.R. Huberty 16. J.D. Isherwood 17. A.F. Pillsbury
	Dept. of Irrigation and Soils, Riverside	18. S.J. Richards
	USDA BPISAE[a] Regional Salinity Laboratory, Riverside	19. M. Fireman 20. L.A. Richards 21. R.C. Reeve
	BPISAE Southwestern Irrigation Field Station, Brawley	22. K. Stockinger
	FS[a] Forest and Range Experiment Station ,Glendora	23. E.L. Hamilton 24. J.S. Horton 25. P.B. Rowe 26. J.D. Sinclair
	SCS[a] P.O. Box 629, Pomona	27. V.S. Aronovici

(continued)

Table 2--Geographic Distribution of workers currently engaged in research on the physics of soil moisture (continued)

Location	Organization[a]	Workers (key to numbers of Table 1)
Colorado	Colorado Agricultural and Mechanical College, Dept. of Agronomy, Fort Collins	1. R. Gardner 2. R.S. Whitney
	Dept. of Civil Engineering	3. W.E. Code 4. N.A. Evans
	USDA BPISAE at Colorado Agricultural and Mechanical College	5. M. Amemiya
	FS Rocky Mountain Forest and Range Experiment Station, Fort Collins	6. L.D. Love
	SCS at Colorado Agricultural and Mechanical College, Fort Collins	7. C. Rohwer
	SCS Grand Junction	8. E.W. Cowley
Connecticut	Agricultural Experiment Station, Dept. of Soils, New Haven	1. H.G.M. Jacobson 2. H.A. Lunt 3. C.L.A. Swanson
Florida	University of Florida, Dept. of Soils, Gainesville	1. S.N. Edson 2. L.C. Hammond 3. G.M. Volk
	Citrus Experiment Station, Lake Alfred	4. I.W. Wander
Georgia	University of Georgia, Dept. of Agronomy, Athens	1. C.W. Domby
Hawaii	University of Hawaii, Dept. of Plant Physiology, Honolulu	1. H.F. Clements
	Dept. of Soils and Agricultural Chemistry, Honolulu	2. G.D. Sherman
Idaho	University of Idaho, Dept. of Agricultural Engineering, Moscow	1. G.L. Corey 2. R.W. Harder 3. Victor I. Meyers
	USDA FS Intermountain Forest and Range Experiment Station, P.O. Box 1839, Boise	4. P.E. Packer
	SCS P.O. Box 635, Boise	5. C.H. Pair
Illinois	University of Illinois, Dept. of Agronomy, Urbana	1. A. Klute
Indiana	Purdue University, Dept. of Agronomy, West Lafayette	1. A.F. Klinge 2. H. Kohnke 3. P.F. Low
	Dept. of Agricultural Engineering, West Lafayette	4. I.D. Mayer
	USDA SCS at Purdue University, West Lafayette	5. H.A. Jongedyk 6. N.L. Stoltenberg
Iowa	Iowa State College, Dept. of Agronomy (Soils), Ames	1. M.W. Bittinger 2. D.D Evans 3. H.P. Johnson 4. D. Kirkham 5. M. Maasland

(continued)

Table 2--Geographic distribution of workers currently engaged in research on the physics of soil moisture (continued)

Location	Organization[a]	Workers (key to numbers of Table 1)
Iowa	Iowa State College, Dept. of Agronomy (Soils), Ames	6. R.W. Rollins 7. J.R. Rundles 8. J. van Schilfgaarde 9. G.O. Schwab 10. A.D. Scott 11. J.F. Stone 12. D. Swartzendruber 13. W. Willis
	Dept. of Agricultural Engineering, Ames	14. R.K. Frevert 15. M.G. Spangler
	Dept. of Agricultural Climatology	16. R.H. Shaw
Kansas	Kansas State College, Dept. of Agronomy, Manhattan	1. W.S. Chepil 2. J.A. Hobbs 3. W.W. Rasmussen
Louisiana	University of Louisiana, Dept. of Agronomy, University Station, Baton Rouge	1. C.E. Scarsbrook
Maine	University of Maine, Dept. of Agronomy, Orono	1. R.A. Struchtmeyer
Maryland	University of Maryland, Dept. of Agronomy, College Park	1. B. Beacher 2. E. Strickling
	USDA BPISAE Agricultural Research Center, Beltsville	3. C.S. Slater
Massachusetts	University of Massachusetts, Dept. of Agronomy, Amherst	1. K.J. Kucinski
Michigan	Michigan State College, Dept. of Soil Science, East Lansing	1. A.E. Erickson 2. H.A. Stolzy 3. H.A. Vollbrecht 4. N.A. Willits
	USDA SCS at Michigan State College, East Lansing	5. G.A. Crabb
Mississippi	USDA FS Southern Forest Experiment Station, Waterways Experiment Station, Vicksburg	1. H.W. Lull
Missouri	University of Missouri, Dept. of Soils, Columbia	1. W.L. Decker 2. C.M. Woodruff
Montana	Montana State College, Dept. of Agronomy and Soils, Bozeman	1. J.C. Hide
	Huntley Branch Station, Huntley	2. T.A. Aasheim
	USDA BPISAE at Montana State College, Bozeman	3. W.E. Larson
Nebraska	University of Nebraska, Dept. of Agronomy, Lincoln	1. T.H. Gooding 2. A.P. Mazurak 3. T.M. McCalla 4. R.E. Ramig 5. H.F. Rhoades 6. J.C. Russel 7. B.R. Somerhalder
	USDA BPISAE at University of Nebraska	8. L. Harris 9. O.W. Howe
	SCS at University of Nebraska	10. F. L. Duley 11. F.B. Hamilton
New Jersey	Rutgers University, Dept. of Soils, New Brunswick	1. G.R. Blake 2. G.D. Brill 3. J.A. Vomicil

(continued)

Table 2--Geographic distribution of workers currently engaged in research on the physics of soil moisture (continued)

Location	Organization[a]	Workers (key to numbers of Table 1)
New Mexico	College of Agriculture and Mechanic Arts, Dept. of Agricultural Engineering, State College	1. E.G. Hanson
	Northeastern Substation, New Mexico Agricultural Experiment Sta., Tucumcari	2. C.G. Painter
	USDA FS Southwestern Forest and Range Experiment Station, Albuquerque	3. E.J. Dortignac
New York	Cornell University, Dept. of Agronomy, Ithaca	1. K. Barley 2. G.H. Bolt 3. R.D. Miller 4. R. Olsen 5. M. Peech
North Carolina	North Carolina State College, Dept. of Agronomy, Raleigh	1. M.J. Gilbert 2. W.D. Kemper 3. J.F. Lutz 4. C.H.M. von Bavel
North Dakota	USDA BPISAE Northern Great Plains Station, Mandan	1. H.R. Haise
Ohio	Ohio State University, Dept. of Agronomy, Columbus 10	1. P.E. Baldridge 2. L.F. Green 3. G.S. Taylor
Oregon	USDA SCS Malheur Experiment Station, Ontario	1. F.M. Tileston
Pennsylvania	Pennsylvania State College, Dept. of Agronomy, State College	1. R.B. Alderfer
	USDA BPISAE Regional Pasture Research Laboratory, State College	2. R.R. Robinson
	FS Northeastern Forest Experiment Station, at Lehigh University, Bethlehem	3. N. Bethlahmy 4. I.F. Reigner
Puerto Rico	University of Puerto Rico, Dept. of Soils, Rio Piedras	1. J.A. Bonnet 2. J. Figarella 3. E. Hernandez-Medina 4. P. Landrau, Jr. 5. M.A. Lugo-López 6. M.B. Martinez 7. G. Samuels
	USDA BPISAE, at University of Puerto Rico, Rio Piedras	8. F. Abruña 9. R. Caro 10. S. Silva 11. J. Vicente-Chandler
Rhode Island	University of Rhode Island, Dept. of Agronomy, Kingston	1. D.A. Schallock
South Carolina	USDA FS Southeastern Forest Experiment Station, P.O. Box 257, Union	1. M.D. Hoover
South Dakota	South Dakota State College, Newell Irrigation and Dry Land Experiment Sta., Newell	1. B.L. Baird
	Dept. of Agronomy, College Station	2. R.E. Campbell 3. L.O. Fine 4. W.C. Moldenhauer

(continued)

Table 2--Geographic distribution of workers currently engaged in research on the physics of soil moisture (concluded)

Location	Organization[a]	Workers (key to numbers of Table 1)
Tennessee (concluded)	University of Tennessee, Dept. of Agronomy, Knoxville	1. W.L. Parks (in cooperation with TVA)
Texas	Agricultural and Mechanical College of Texas, Dept. of Agronomy, College Station	1. J.B. Page
	Texas Agricultural Experiment Sta., Beaumont	2. R.E. Cheaney
	Texas Agricultural Experiment Sta., Weslaco	3. M.E. Bloodworth 4. P.E. Ross
	USDA BPISAE at A. and M. College of Texas, College Station	5. E.R. Lemon
Utah	Utah State Agricultural College, Dept. of Agronomy, Logan	1. L. Cavazza 2. J.L. Haddock 3. S.A. Taylor 4. R. Uhler
	Dept. of Irrigation and Drainage, Logan	5. D.K. Fuhriman 6. V.E. Hansen 7. O. W. Israelsen
	Dept. of Physics, Logan	8. Willard Gardner
	USDA SCS Utah State Agricultural College, Logan	9. C.W. Lauritzen
Virginia	Virginia Polytechnic Institute, Dept. of Agricultural Engineering, Blacksburg	1. W.L. Turner 2. P. Walker
Washington	State College of Washington, Dept. of Agronomy, Pullman	1. G.H. Cannell 2. W.H. Gardner 3. E. W. Hope 4. J.C. Hsieh 5. P.P. Rowe 6. P.R. Rowe
	USDA BPISAE Irrigation Experiment Station, Prosser	7. W.O. Pruitt 8. J.S. Robins
Wisconsin	University of Wisconsin, Dept. of Soils, Madison	1. S.J. Bourget 2. D. Elrick 3. R.J. Hanks 4. C.B. Tanner
Wyoming	University of Wyoming, Dept. of Agronomy, Laramie	1. W. McNab Miller

[a] Abbreviations not otherwise indicated are as follows: BPISAE, Bureau of Plant Industry, Soils and Agricultural Engineering; FS, Forest Service; SCS, Soil Conservation Service; and USDA, United States Department of Agriculture.

Table 2 is supplementary to Table 1 and contains the names of investigators, together with their affiliations and addresses. Individuals engaged in the research indicated in Table 1 are there listed by numbers, preceded by an abbreviation of the name of the state or territory in which they work. Names are found opposite the numbers that are listed, geographically, in Table 2. Replies were also received from nine states where no work of this nature is now in progress.

The Committee gladly acknowledges the kind cooperation of all who contributed information used in the Report; and especially to N. Collis-George for his aid in the compilation of this report.

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DISCUSSION OF

"THE GEOPHYSICAL APPLICATIONS OF GRAVITY ANOMALIES"
by W. HEISKANEN

[Trans., v. 34, pp. 11-15, 1953]

G. D. Garland (Dominion Observatory, Ottawa, Ontario, Canada)--One hesitates to differ with Heiskanen on the subjects of gravity and isostasy, as he himself has contributed so much to those fields. There is, however, one phase of his recent paper which provides ground for discussion, and that is the application of Bouguer anomalies to general studies of the Earth's crust.

As a specific example, Heiskanen gives the Bouguer anomalies that would be observed over a completely compensated conical ocean island for crustal thicknesses of 30 and 40 km. For a crustal thickness of 30 km, the anomaly decreases from + 340 mgal at large distances to + 16 mgal over the centre ~~of the~~ island (Fig. 1). The author concludes that "the Bouguer anomalies on the island are small because the negative effect of the root of the island compensates for most of the positive effect of the antiroot of the ocean" and that "the Bouguer anomalies cannot be used to explain the detailed structure of the Earth's crust under the ocean island." It would appear worthwhile to take this "observed" Bouguer anomaly as a starting point and to investigate what can be deduced from it.

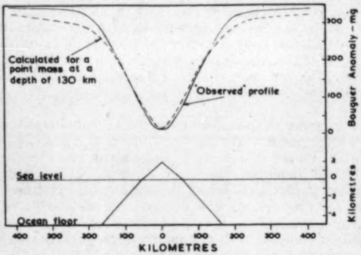

Fig. 1--Gravity field for a conical mountain

Taking the undisturbed oceanic level of anomaly to be + 340 mgal, the effect over the island is in reality a negative anomaly of 324 mgal. Now in computing the Bouguer anomaly, allowance is made for the attraction of material above sea level at land stations, and for the deficiency in mass in the ocean at sea stations. Since the island is assumed to be of normal crustal density, there remains in the Bouguer anomaly no effect due to the island itself, and the negative anomaly must be an expression of conditions beneath the level of the ocean floor.

The first fact which can be determined from the Bouguer anomaly is the actual value of the mass deficiency necessary to produce the effect. This may be computed, without any limiting assumptions as to the distribution of the mass, from the integral of Gauss, namely

$$M = (1/2\pi G)\iint \Delta g \, ds \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, (1)$$

where M = the total anomalous mass, G = the gravitational constant, and Δg = the Bouguer anomaly.

The integral is evaluated over the surface of the Earth to the limits of the detectable anomaly. The application of this theorem of Gauss to gravity interpretation was first described in detail by HAMMER [1945].

In the present case, integration of the circular, closed anomaly over the island gives a total mass deficiency of approximately 4.0×10^{17} kg. The volume of the island below sea level is approximately 1.96×10^{20} cc, while that above sea level is about 7.2×10^{18} cc. Assuming the crustal density to be 3.0 grams per cc, and the density of sea water to be 1.0 grams per cc, the excess mass of the island is about 4.1×10^{17} kg. Our first conclusion is, therefore, that the island is very nearly in complete equilibrium with the mass deficiency beneath it, regardless of the depth or type of compensation.

Further deductions from the gravity anomaly cannot be made with the same generality, but certain limits may be placed on the position of the disturbing mass. A point mass situated at a depth of 130 km below sea level gives a curve which approximates quite closely to the observed profile (Fig. 1). As this is the most concentrated form possible for the disturbing mass, it is highly unlikely that the center of attraction of the actual structure is deeper than 130 km. We may therefore state that somewhere between the ocean floor and a mean depth of 130 km there is a mass deficiency of 4.0×10^{17} km. This is all that the gravitational field at the Earth's surface can tell us, without further assumptions, regardless of how the anomalies are computed.

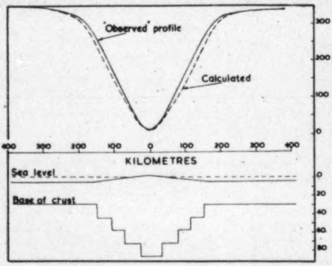

Fig. 2--Sub-crustal structure approximating "observed" gravity field

If we assume the density difference between the anomalous structure and its surroundings, and some facts relating to the position or shape of the body or both, we may proceed to find the most probable solution under these assumptions, either by a cut-and-try process or the more elegant direct methods of BULLARD and COOPER [1948], GRANT [1952], and others. As an example, assuming a crustal thickness of 30 km, a density contrast of 0.3 gm per cc at the base of the crust, and a structure immediately under the crust, it is possible to construct the body shown in Figure 2. The anomaly due to this body, which consists of four discs of equal thickness, whose diameters are successively smaller with depth, was estimated by means of the solid angle chart of NETTLETON [1942]. It is in fair agreement with the observed profile, and could be made to fit still more closely by adjusting the assumed structure. In other words, the Bouguer anomaly has allowed us to find the approximate form of the island roots under the assumption made above.

In view of what has deduced from the Bouguer anomaly "observed" over the island, Heiskanen's remark that it cannot be used in this case seems a little unfair. On the other hand, it is not the purpose of this note to suggest that Bouguer anomalies be used exclusively. In general, one cannot analyze the Bouguer anomaly over every oceanic island, mountain range, or other structure, with the detailed methods we have employed here, in order to test a theory of isostatic compensation. The isostatic anomalies do allow different theories to be tested in different parts of the world, as Heiskanen has shown. The great beauty of the Bouguer anomaly is that it is computed with the very minimum of assumptions, and, as JEFFREYS [1950] has stated, "all the information gravity can give about the distribution of density is summed up in the Bouguer anomaly."

W. Heiskanen (Institute of Geodesy, Photogrammetry, and Cartography, Ohio State University, Columbus, Ohio, Author's closure)--As I had through the generosity of the American Geophysical Union the opportunity to deliver a paper at the Union's annual meeting in 1952, and to publish it in the *Transactions*, I dealt with the geophysical applications of gravity anomalies because some scientists have during the last three decades misused gravity anomalies in explaining the behavior of the Earth's crust. Most confusion has arisen because only Bouguer anomalies have been used. These anomalies lead in general to wrong results in the "Randsenken" of mountain chains at the oceanic margins and in the ocean islands, or, in general, in such areas where topography changes rapidly from point to point. This is, of course, due to the fact that the isostatic compensating layers have a remarkable effect on gravity anomalies very far in the horizontal direction. This "horizontal effect" is too often neglected when interpreting Bouguer anomalies.

I know very well that Bouguer anomalies can in some cases lead to approximately right results. In fact, before the publications of BULLARD and COOPER [1948] and of GRANT [1952], SCHWINNER [1929], and SALONEN [1932] used Bouguer anomalies, the former in interpreting the gravity anomalies in the east Alps, the latter in the west and central Alps.

Still some small remarks might be necessary. When Garland says that the disturbing mass in the case of my fictitious ocean island can even be a mass point at depth of 130 km, it is, of course, only a pure mathematical figure without any geophysical correspondence. Everyone knows that the compensating mass of so large an island cannot be a masspoint. It must have quite extensive horizontal dimensions and it consequently must be much closer to the Earth's surface. Therefore, his sentence, "This (disturbing masses are somewhere between the depths 0 to 130 km) is all that the gravitational field at the Earth's surface can tell us without further assumptions regardless of how the anomalies are computed,'' has very small significance.

I agree also in a way with Garland's quotation from Jeffreys', ''All the information gravity can give about the distribution of density is summed up in the Bouguer anomaly.'' However, it is only summed up so that it is very difficult, in many case impossible, to read in the right way the dim message of the Bouguer anomaly.

In broad lines, Garland appears to be in agreement with me, since he is of the opinion that Bouguer anomalies cannot be used exclusively ''to test a theory of isostatic compensation.'' I hope that he agrees with me in the following facts: (1) Isostatic equilibrium prevails in broad lines. (2) Bouguer anomalies can show qualitatively what areas are in broad lines in isostatic equilibrium. (3) Bouguer anomalies are very useful for instance for the exploration purposes but can too easily lead to wrong conclusions as far as the general geophysical studies are concerned. (4) Details of the isostatic equilibrium and deviations from it can be obtained only through the isostatic reductions. (5) Several publications (which might not be necessary to list here) show how easy it is to misuse the Bouguer anomalies.

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DISCUSSION OF

''ACCELERATED MOTION OF A SPHERICAL PARTICLE''
by M. R. CARSTENS

[Trans., v. 33, pp. 713-721, 1952]

Norman H. Brooks (Department of Civil Engineering, California Institute of Technology, Pasadena, Calif.)--In considering the accelerated motion of spheres in a viscous fluid, the author has restricted himself to consideration of only simple harmonic motions of the fluid field and the sphere. The author's equation of motion (Eq. 11) for a suspended sphere is true only when the solution yields a relative displacement $(x - a)$ which is sinusoidal in time. Otherwise, the apparent mass factor k, and the damping coefficient A have no meaning, because they are both based on the Stokes solution for an oscillating sphere given in LAMB [1945, see References at end of published paper, p. 721]. Both k and A are functions of the circular frequency ω as they are defined by (1), (2), and (3).

As an example of the inadequacy of (11) for general purposes, one may consider the effect of adding the gravity force $-(M_o - M)g$ to the right side of (11). Using $a = a_o \sin\omega t$, the solution will be just as given in (12) except for an added term; thus we get

$$x = x_o \sin(\omega t + \alpha) - [(M_o - M)g/A]\, t$$

The superposed settling velocity appears to be $(M_o - M)g/A$ where A depends on ω.

This is clearly incorrect, because the settling velocity has a constant value w which is independent of the frequency ω. This follows directly from the fact that the Navier-Stokes equations are linear in pressure and velocity when all velocity product terms (that is, convective acceleration terms) are neglected, according to the Stokes approximation. Thus the solution $x_1 = -wt$ can be superimposed on any other solution (which the author correctly did subsequently in deriving ϵ_s).

TCHEN [1947, chap. 4 and 5] has obtained a general equation of motion which is not based upon any presuppositions about the solution and might be given in place of (11). Tchen started with the integro-differential equation for the rectilinear accelerated motion of a sphere derived by BASSETT [1888, p. 291] and BOUSSINESQ [1903, p. 238]. Again all velocity product terms were neglected. In the author's notation this equation, including the gravity term, may be written as

$$(M_o + M/2)\ddot{x} = -3\pi\mu d\,[\dot{x} + (d/2\sqrt{\pi\nu})\int_{t_o}^{t} dt_1\,\ddot{x}(t_1)/\sqrt{t-t_1}\,] - (M_o - M)g \ldots\ldots\ldots (21)$$

where the entire system is at rest until the instant $t = t_o$. For convenience t_o may be taken as $-\infty$. From this, Tchen derived the equation of motion for a small sphere in a moving fluid

$$(M_o + M/2)\ddot{x} = (3/2)M\ddot{a} - 3\pi\mu d\left\{\dot{x} - \dot{a} + (d/2\sqrt{\pi\nu})\int_{-\infty}^{t} dt_1\,[\ddot{x}(t_1) - \ddot{a}(t_1)]/\sqrt{t-t_1}\right\} - (M_o - M)g \ldots. (22)$$

He solved this equation for the case of simple harmonic fluid motion and obtained the same result as the author's (15).

By skillful manipulations which eliminated the integral term involving $\dddot{x}$, Tchen arrived at the following linear second-order differential equation for $\dot{x}$

$$\dddot{x} + 2K\ddot{x} + (K^2 + \sigma^2)\dot{x} = G(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

where

$$G(t) = -\alpha_o w + \alpha_o\dot{a}(t) + \alpha_1\ddot{a}(t) + \alpha_2\dddot{a}(t) - \alpha_3\int_{o}^{\infty} dt_1\,\dddot{a}(t-t_1)/\sqrt{t_1} \ldots.. (24)$$

The various coefficients in (23) and (24) may be conveniently defined in terms of the two constants

$$\gamma = 12\,\nu/d^2, \quad s = 3\rho/(2\rho_s + \rho) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (25)$$

and are as follows

$$\left.\begin{aligned} \alpha_o &= \gamma^2 s^2 \\ \alpha_1 &= \gamma s\,(1 - 2s) \\ \alpha_2 &= s \\ \alpha_3 &= (\sqrt{3\gamma/\pi})\,s\,(s-1) \\ K &= \gamma s\,(1 - 3s/2) \\ \sigma^2 &= \gamma^2 s^2 - K^2 = 3\gamma^2 s^3\,(1 - 3s/4) \end{aligned}\right\} \ldots\ldots\ldots\ldots\ldots (26)$$

Also w, the Stokes settling velocity, is given by the familiar formula

$$w = g\,(\rho_s - \rho)\,d^2/18\mu$$

The general integral solution of (23) is

$$\dot{x}(t) = (1/\sigma)\int_{o}^{\infty} d\eta\,e^{-K\eta}\sin\sigma\eta\,G(t-\eta) \ldots\ldots\ldots\ldots\ldots (27)$$

Equation (27) will give the correct particle velocity $\dot{x}(t)$ for any arbitrary fluid velocity $\dot{a}(t)$, provided only that the convective acceleration terms are small, as was originally assumed.

In the derivation of (19) for ϵ_m, the author implies that ϵ_m is identical with the coefficient of diffusion of fluid particles (let this be called ϵ_o). Fluid particles or molecules in solution are transported bodily in a fluid element, and, except for a relatively insignificant amount of molecular diffusion, they are carried with the fluid element wherever it goes. But, on the other hand, momentum is continually being transferred from one fluid element to its neighbors by pressure differentials and viscous shear. Thus the momentum carried by a parcel of fluid may be expected to vary continuously during its excursion from one point to another. TAYLOR [1932, p. 685] pointed out the variability of momentum due to pressure fluctuations as a weakness of Prandtl's momentum transfer theory when he advocated his vorticity transfer theory to obviate this difficulty. BURGERS [1951, chap. 5] considers the viscous transfer of momentum between adjacent elements more important than the pressure forces in his derivation of the diffusion coefficient for momentum.

Because of these two special factors impeding momentum transfer, this writer believes that it is quite reasonable to presume that the diffusion coefficient for momentum (ϵ_m) is less than the diffusion coefficient for particles of the fluid itself (ϵ_o).

Consequently, the author would be nearer to the truth to give (20) as

$$\epsilon_s/\epsilon_o = (x_o/a)^2 \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (28)$$

Thus, for sediment in water, $\epsilon_s/\epsilon_o < 1$ (since $x_o < a_o$ for $\rho_s > \rho$), but since $\epsilon_m/\epsilon_o < 1$ also, it is not all clear when $\beta = \epsilon_s/\epsilon_m$ is greater than or less than one.

But, whether or not (19) should give the diffusion coefficient for momentum (ϵ_m) or fluid particles (ϵ_o), there is some question about the validity of the way in which the author has tried to derive diffusion coefficients from the equation of motion of a suspended particle. The argument the author follows on page 719 is based on the concept of a discontinuous mixing process with the use of some sort of mixing length, and with the assumption that the fluid elements carry the same concentration of sediment as the mean concentration at the starting point. This Prandtl type of approach is often satisfactory for engineering purposes where the interest is in some average bulk property like concentration of sediment. However, it is hardly a good framework in which to utilize detailed information about the behavior of individual particles. At best, one can talk only of a loosely defined "average behavior" at some representative frequency of a simplified type of motion; and, after all, if a body of fluid simply oscillates up and down with $a = a_o \sin \omega t$, so that the motion of particles in the fluid is $x = x_o \sin(\omega t + \alpha) - wt$, there is certainly no turbulent diffusion. Diffusion occurs only because the turbulent velocities of a fluid element are not periodic in any simple sense.

To make use of the equations of motions of a small particle in suspension (23) to (26), it seems more reasonable to consider diffusion as a continuous process, expressing the diffusion coefficients in terms of integrals of Lagrangian correlations. TCHEN [1947, chap. 4 and 5] used this approach and with (27) calculated the integral of the Lagrangian correlation for the sphere velocity in terms of the same integral for the velocity of the fluid surrounding the particle. Neglecting the effect of gravity, the integrals are equal for any general type of turbulent motion.

Tchen's results are reported in detail by BURGERS [1951, chap. 5] who carries the development still further. Results of theirs which differ from the author's are summarized very briefly here. (1) $\epsilon_s \doteq \epsilon_o$ if the particles generally stay well within their respective fluid elements so that the relative motion can be adequately described by (27). This is true regardless of the type or frequency of the fluid oscillations. This assumption is probably quite accurate for silt and clay in suspension. (2) Actually $\epsilon_s < \epsilon_o$ only by virtue of the fact that sediment particles slip from one fluid element into another in the course of their motion. The amount of this slippage and the ratio ϵ_s/ϵ_o depends on the nature of the motion and size of the fluid elements carrying the sediment; this information cannot be deduced from the equation of motion which simply relates x to a. (3) $\epsilon_m < \epsilon_o$, because of the role of viscous forces transferring momentum between fluid elements. (4) $\epsilon_s > \epsilon_m$ ($\beta > 1$) and $\epsilon_s < \epsilon_m$ ($\beta < 1$) are both physically plausible cases. For very fine material it is reasonable to expect $\epsilon_s > \epsilon_m$, because $\epsilon_s \doteq \epsilon_o$.

Hence this writer is unable to accept (20) which implies that β is always less than unity for particles heavier than the fluid.

M. R. Carstens (School of Civil Engineering, Georgia Institute of Technology, Atlanta, Ga., Author's closure)--The experimental program reported concerned a single oscillating sphere in a fluid at rest. The experimental results are presented graphically in Figures 2 and 3. In an elementary manner these results were applied to the case of a spherical particle in an oscillating fluid. Brooks' remarks are confined to this subsequent analysis and not to the experimental program.

The mechanism of suspended-sediment transportation is extremely complex. The problems can be classified in three categories: (1) the description of the fluid motion; (2) the relationship between the fluid motion and the particle motion; and (3) the description of the particles. The description of the fluid motion is very incomplete despite the great amount of analytical and experimental work of the past 30 years. The result is that the present statistical theory of turbulence is mainly a qualitative tool. There have been practically no studies correlating the particle motion with the fluid motion. A considerable amount of work has been done with the particles in the determination of the shape, size, surface condition, and other factors. In view of the complexity of the suspended-sediment transportation process, it is understandable that simplifications, such as the use of the settling velocity to describe the sediment particles and the use of the Fickian diffusion concept (16), are extensively employed.

The very complexity of the suspended-sediment transportation process is an incentive for a simultaneous analysis of the three categories. Ultimately, a description of the transporting fluid motion will be necessary before a general solution of the mechanism of sediment transportation can be considered to exist. Lacking even this knowledge, the research worker is forced to make drastic simplifying assumptions. In this case the assumptions of spherical particles, of uniformly sized particles, of the absence of adjacent-particle interference, and of simple harmonic motion in the vertical direction would appear to preclude a solution of any significance. Although such a solution may fail to indicate correct numerical magnitudes, it may correctly indicate the importance of the individual variables and the order of magnitude of the result. For instance, in the hypothesized situation the value of the amplitude ratio x_0/a_0 and the value of β was found to be independent of the absolute magnitude of the fluid amplitude. Experimental studies will be needed in order to test the validity of this conclusion in more realistic diffusion motions.

Thus, from this study the conclusion is that the frequency of motion is a prime variable, whereas the absolute value of the amplitude is of no significance in the determination of the value of β. In the discusser's conclusion (1) the exact opposite statement is presented. A portion of the statement is $\epsilon_s = \epsilon_0$ if the particles generally stay well within their respective fluid elements . . . Such a condition is impossible since a diffusion process is one in which both fluid particles and the foreign particles must be transported to other fluid elements or eddies. It is further implied that (27) will be indicative that $\epsilon_s \doteq \epsilon_0$, whereas it will be by means of (27) that the magnitude of ϵ_s/ϵ_0 can be predicted.

In regard to the discusser's conclusion (2), it is correctly stated that $\epsilon_s \neq \epsilon_0$ only by virtue of the relative motion of the particle and the surrounding fluid. Thus ϵ_s/ϵ_0 is a direct function of the slippage between the particle and the fluid. The ratio of the particle amplitude to the fluid amplitude x_0/a_0 is a measure of this slippage. It can only follow that ϵ_s/ϵ_0 must be a function of the amplitude ratio x_0/a_0.

The discusser's conclusions (3) and (4) are valid. A frequent assumption is that $\epsilon_m = \epsilon_0$. However, the experimental studies of CORRSIN [1943] with the diffusion of heat in an axially symmetric jet and the studies of HINZE and VAN DER HEGGE ZIJNEN [1949] with the diffusion of a gas and heat in an axially symmetric jet have indicated that ϵ_0 is slightly greater than ϵ_m. Consequently, the ratio as used in this paper must be considered to be the ratio of the sediment diffusion coefficient and the fluid diffusion coefficient ϵ_s/ϵ_0.

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DISCUSSION OF

"COMPLICATED WELL PROBLEMS SOLVED BY THE MEMBRANE ANALOGY"

by VAUGHN E. HANSEN

[Trans., v. 33, pp. 912-916, 1952]

Raphael G. Kazmann (Fricke and Kazmann, Consulting Engineers, Stuttgart, Ark.)--This paper is a distinct contribution to the methodology of solving problems of steady-state flow to well systems. It will undoubtedly be read with interest by engineers and others in the field of applied hydrogeology.

Although elegant solutions to the simpler problems of steady-state flow to wells have long been available (such as the classic derivation of the equation defining drawdowns around a well centered in a circular island which, in turn, is located in a lake), it is only in the past few years that multiple-well systems operating in aquifers (which are characterized by complex hydrogeological boundaries) have been at all amenable to engineering solution.

Three principal methods are now available to the practicing engineer in his quest for usable solutions to the problems involved in the design and operation of multiple-well systems (in addition to the judicious application of well-formulas). (1) The model study, along the lines of the work done at the University of Illinois Engineering Experiment Station [BABBITT and CALDWELL, 1948, see References at end of paper, p. 916]. (2) The membrane analogy study, as outlined by Hansen's excellent paper. (3) The use of "relaxation methods"--a mathematical technique which combines arithmetic, geometry, and pertinent information defining the boundaries to determine the contours of the piezometric surface. This approach, outlined by R. V. Southwell in his book, Relaxation Methods in Theoretical Physics, is in use by several workers in the field of ground water, although publication of the results is yet to come.

Each of these methods has its own unique advantages and limitations. Although the writer has not had personal experience with the first two, he has found relaxation technique to be most productive of useful results and, upon considering Hansen's paper, believes that Methods (2) and (3) above could be satisfactorily combined.

Hansen would undoubtedly add substantially to the utility of his paper if, in his closure, he would discuss at convenient length:

(1) Whether experiments similar to those described in the paper have been conducted where, instead of a circular "recharge" boundary, some portion of the circular boundary has been replaced by a circle-segment across which no flow occurs. That is, the slope of the piezometric surface across this segment is horizontal and its elevation is determined by the boundary condition and the drawdown at the well. In the experiment described in the paper the elevation of the boundary was held constant at all points and the slope of the piezometric surface at all points on the boundary was free to assume the value necessitated by the displacement of the probe which represented the drawdown at the well.

(2) According to the paper, the distance from the well to the outer boundary was 100 times the well radius. In practice the well radius may be one or two feet, or 100 ft in the case of a horizontal collector, but the distance to the nearest boundary may be measured in miles. The distance between wells in a well-field will normally range from several hundred to several thousand feet. In view of these dimensions, has it been found feasible, in solving specific problems, to retain undistorted geometric relationships without the use of unduly large membranes?

Vaughn E. Hansen (Utah State Agricultural College, Logan, Utah, Author's closure)--In lieu of the breakdown of methods now available for the solution of complicated multiple-well problems presented by Kazmann in his discussion, the writer proposes to group the methods into the following three basic catagories: (1) formulas, (2) numerical computation by successive approximation commonly referred to as the relaxation method, and (3) model studies.

Several model approaches are now available. The appropriate method depends upon the particular problem to be solved. Perhaps the oldest method is the use of a porous media such as sand. More recent developments utilize an electrical conductor, either liquid or solid. The rubber membrane as proposed by the author is the most recent method. Model solutions have been made utilizing combinations of these techniques.

The rather ingenious use of models by CHONG-HUNG ZEE [The use of combined electrical and membrane analogies to investigate unconfined flow into wells, doctoral dissertation, Irrigation and

Drainage Dept., Utah State Agric. Coll., 1952] has extended considerably the scope of the work reported in this paper. Zee used a combination of the membrane analogy as proposed by the author and the electrical analogy which is already in common use to obtain the free surface for unconfined flow to the well.

In answer to Kazmann's first question, the writer knows of no membrane model studies of the boundary conditions he describes. In response to his inquiry regarding the use of the membrane to solve specific problems involving large distances, the writer does not believe the membrane is the correct tool to use when dimensions of several thousand feet or several miles are involved. The membrane should be considered as another tool to augment present techniques used in the solution of well problems. It must be used wisely if its utility is to be realized. When large distances are involved the well formulas will probably yield the best solution. The major utility of the membrane analogy is for multiple-well problems where the drawdown of one well markedly alters the drawdown pattern of adjacent wells.

DISCUSSION OF

"RAINFALL AND TOPOGRAPHIC FACTORS THAT AFFECT RUNOFF"

by W. D. POTTER

[Trans., v. 34, pp. 67-73, 1953]

Ralph W. Powell (Department of Mechanics, Ohio State University, Columbus, Ohio)--A great deal of study has been put on developing methods of estimating the peak runoff that may be expected in a given number of years from medium- and large-sized drainage areas. The maximum rate of runoff to be expected from small drainage areas is an equally important matter, because of its bearing on the design of culverts and the spillways for small reservoirs, but one which has received much less attention. Thanks are therefore due the author for making the results on his studies generally available.

Some years ago PETTIS [1927] proposed a formula for probable 100-year peak runoff which made it depend solely on the probable rainfall and on the average width of the drainage basin. He felt that the slope had no appreciable effect on the higher flood flows from areas between 1000 and 10,000 sq mi, and little effect on areas down to 100 sq mi. This seems doubtful, but it does seem that a fan-shaped drainage basin with several large tributaries entering not far above the point being considered would have a much larger peak runoff than a long narrow drainage basin of the same area and channel slope. This is partly because in the first basin, in the case of a short intense rain, the peak flow from a large part of the drainage area would reach the point in question nearly simultaneously; and partly because for rains continuing until all parts of the basin are contributing, the time of concentration is less, so that the maximum rainfall rate to be considered would be that for a shorter length of time, and therefore of a higher intensity.

The author has kindly supplied the length of stream for each of the 51 drainage areas considered. This was taken as the length of the drainage area which of course introduced an error, probably serious for only a few of the smaller areas. A dimensionless length-ratio, $R = L/\sqrt{A}$, (where L = length in miles) was computed for each drainage area, and an equation $q_{c2}/q_{c1} = kR^m$ assumed, where q_{c1} is the peak rate of runoff as computed by the author's formula, and q_{c2} is the same as corrected for the effect of the length-ratio. By least squares, m was found to be 0.1514 and k = 0.8595. This results in the formula

$$\log q = -1.487 + 0.170 \log A - 0.554 \log T + 0.929 \log P + 0.449 \log S + 0.151 \log R$$

The probable error by this formula was computed to be 12 pct, while the author's formula gave 12.8 pct. The improvement is hardly enough to be worth the trouble, but it might be that using L as the additional variable and computing the multiple correlation de novo would have given a better fit. It seems very unlikely, however, that the coefficient of log L would have turned out to equal the negative of the coefficient of log A, so that the average width of the basin could replace A and L in the equation.

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PETTIS, C. R., A new theory of river flood flow, published privately, 1927; The probable 100-year flood, published privately, 1932; Flood probability formula modified to simplify application, Engr. News-Rec., v. 112, pp. 804-805, 1934.

W. D. Potter (Bureau of Public Roads, Washington 25, D. C., Author's closure)--I am in complete accord with Pettis and Powell in their statements that watershed shape is a significant factor affecting the magnitude of peak rates of runoff.

As pointed out by Powell, it is the difference in travel time of the runoff that is primarily responsible for the difference in peak rates between watersheds of varying shapes. Since my T-factor (channel length divided by the square root of slope) is indicative of this travel time, it follows that it should also be indicative of watershed shape. Thus a fan-shaped watershed would have a shorter travel time, a larger peak rate of runoff, and a smaller T-factor than a long, narrow watershed of the same area and channel slope.

The T-factor has an advantage over a shape factor that is based wholly on the length and width of a watershed in that the T-factor is also indicative of channel storage. For example, a watershed having a long meandering drainage channel would have more channel storage, a smaller peak rate of runoff, and a larger T-factor than a watershed of the same area and shape but having a shorter stream channel.

Powell's inability to improve my regression equation significantly by the addition of a shape factor is a substantiation of my claim that the T-factor, when considered with area and peak rate of runoff, is indicative of watershed shape.

DISCUSSION OF

"EXPANSION AND INCREASE IN PERMEABILITY OF CARBONATE ROCKS ON HEATING"

by JOHN C. MAXWELL and PETER VERRALL

[Trans., v. 34, pp. 101-106, 1953]

Clifford A. Kaye (U. S. Geological Survey, Spokane, Wash.)--Maxwell and Verrall's interesting study raises a thought. If limestones expand on heating and thereby receive a permanent set, as this paper demonstrates, do we not have here a means of determining the maximum temperature to which a particular limestone was ever subjected and indirectly thereby its maximum depth of burial or other geothermal events in its history?

If a limestone, once heated to a given temperature, experiences little or no further expansion on reheating until that temperature has been exceeded (the authors do not make this perfectly clear), and if the expansion is truly permanent, then it seems that any limestone is a maximum recording thermometer, and that by suitable tests the maximum paleothermal temperature can be determined. The method of determining this temperature would follow essentially the tests described in Maxwell and Verrall's paper: heating samples of limestone and measuring their expansion, either at regular temperature intervals or preferably continuously. The maximum paleotherm would become manifest where the rate of expansion suddenly increased or, more ideally, at the point where expansion begins. Referring, however, to the temperature-expansion (T-E) curves accompanying the paper, it is obvious that the T-E curves for a given limestone differ with confining pressure. Since the maximum paleotherm in most limestones would have occurred at pressures greater than atmospheric, the question is raised whether for the correct determination of this temperature, the corresponding pressure must not also be used in the test. For example, in Figure 5 (St. Genevieve limestone, oolitic) the breaks in the T-E curves occur approximately at the three following temperatures for the three corresponding pressures: 300° C., atmospheric pressure; 400° C., 5,000 lb/in^2; 200° C., 10,000 lb/in^2. These temperatures, however, are probably too high for these pressures (1) if the geothermal gradients in the Earth's crust at the time these limestones were at their maximum burial accorded with those of our present knowledge and (2) if these rocks did not receive heat from any anomalous source. The pressure-temperature factor, therefore, would probably have to be carefully appraised for every limestone on the basis of its inferred geological history. Perhaps the best approach to determining the maximum paleotherm is to set the test up as close to the geologically inferred maximum P-T conditions as possible and to refine the testing and measuring equipment to permit continuous expansion measurements during the course of the heating, and particularly in the lower temperature range (between 60° and 200° C.). This procedure, however, might conceivably show that tests run at atmospheric pressures rather than at elevated pressures give the most credible results and that one can interpret directly from such data the maximum depths of burial and indirectly the amount of heat received from the kinetic energy of tectonic movements and from anomalous heat concentrations. The validity of this analysis will, admittedly, be strictly limited to those limestones that have not undergone recrystallization or other radical changes in their crystalline composition and structure since the advent of the maximum paleotherm. This probably means that the older limestones will not yield up any secrets to such simple laboratory tests as these.

Finally, it is of interest to note that CASAGRANDE [1936] called attention to a somewhat related phenomenon when he described the self-recording strain-gage mechanism of compacted clays. According to Casagrande, certain clays retain the compaction corresponding with whatever pressures they previously had been subjected to, and these pressures can be determined by an appropriate test. This test is similar in principle to that proposed for measuring the maximum paleotherm of limestones.

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CASAGRANDE, A., The determination of the preconsolidation load and its practical significance, Proc. First Internat. Conf. Soil Mechanics, v. 3, p. 60, 1936.

John C. Maxwell and Peter Verrall (Department of Geology, Princeton University, Princeton, N. J., Authors' closure)--Kaye's proposal is most interesting and will be of considerable importance if found to be workable.

The amount of permanent expansion produced by heating carbonate rocks in our experiments depends on total temperature rise, degree of preferred orientation of the calcite crystals, and perhaps also on average grain size. Kaye is correct in pointing out that a specimen, once heated to a given temperature, undergoes little or no further expansion on prolonged heating or reheating until that temperature has been exceeded. This is the behavior to be expected if the permanent expansion results from the jostling of the thermally anisotropic calcite crystals against one another. In tests at atmospheric pressure, limestones and travertine which had never been buried more than a few hundred feet reacted much the same as crystalline marbles. The important point is that the temperature is raised rather abruptly a hundred degrees or so. Previous thermal history seems to exert little or no direct control.

"Permanent" expansion induced in deeply buried carbonate rocks by a sudden temperature rise probably disappears shortly afterward due to recrystallization, creep, or other adjustment mechanism. Marbles from contact zones, for example, are not noted for their porosity (though few measurements are available and this assumption may be incorrect). While it is certainly true that a carbonate rock in place in the Earth would have to be heated above its normal temperature to produce "permanent" expansion, it seems unlikely that a rock, when exposed by erosion, will retain any "memory" of its original higher temperature environment. This is only our opinion, however, and has not been checked experimentally.

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LETTERS TO THE EDITOR

RIVER MEANDERS AND VORTICITY THEOREM

The serpentine windings of rivers, which in certain reaches attain a remarkable symmetry and are then called meanders, must represent one aspect of the tendency for establishment of quasi-equilibrium in natural streams. With the increase in knowledge of the interaction of forces operating in rivers, this tendency toward equilibrium has assumed a greater significance.

The current interest in these equilibrium processes is indicated by numerous recent papers dealing with the work of streams. The problem of river meanders has figured prominently in this recent literature. Discussions of meander mechanics have presented some conditions which are necessary but not sufficient to explain the origin of the serpentine curves of rivers.

A theory of meanders must provide an explanation for a number of observed relations. John P. Miller, in a personal communication, reports that while working on the glaciers of Alaska he observed streams of clear water, that is, without sediment load, which developed true meanders under some circumstances. Many tidal estuaries also meander where sediment load is negligible. The mechanics of meanders must, therefore, include some physical principle which does not depend on a load of debris. An adequate theory should explain why some rivers meander and others do not, and why meanders tend to form predominantly in downstream reaches rather than in the headwaters. It is logical also to expect that a given isolated curve in an otherwise straight channel imposes some effect on the flow. This effect must carry into the initially straight reach downstream a tendency for the development of a reverse curve; that is, a curve in the opposite direction from the initial one. A meander theory should provide such a mechanism.

The present note discusses in preliminary form a theory of the mechanics of river bends. The hypothesis is based on an application of the theorem of Kelvin that the absolute circulation of a closed fluid curve is conserved in an autobarotropic fluid. Though the hypothesis does not give definitive answers to the questions stated above, it at least provides some reasoning about each and suggests a direction for further work.

Conservation of angular momentum in a two-dimensional case--When water flows in a curved flume, the tendency for conservation of angular momentum can be observed providing that momentum is not dissipated through turbulent eddies or bed friction. A deep, narrow flume satisfies this condition. In the curved portion of such a flume, angular momentum is conserved and consequently the velocity will be distributed laterally across the flume cross-section in accordance with the equation

$$vr = \text{constant}$$

where v is the velocity at any point and r is the radius of curvature of the streamline at that point. This distribution of velocity is called "potential flow" and represents a condition in a fluid analogous to the conservation of angular momentum in mechanics.

This was demonstrated by WATTENDORF [1935] using a flume deep enough with respect to width for bed effects to be nearly eliminated. He showed that water flowing from a straight into a curved reach conserves its angular momentum and the velocity becomes redistributed so that the highest velocity is near the inside or convex wall where the radius of curvature of the streamline is shortest. There is thus a velocity gradient across the channel or a horizontal shear in the velocity field.

It is reasoned, therefore, that if the water leaving the curved reach of a meander enters the succeeding straight reach (crossover or point of inflection of the wave) with shear in the velocity field, this shear existing in the straight reach would, by the conservation of circulation, tend to cause the flow to develop curvature. The curve would be of such sense that the center of curvature would be on the side of the highest velocity; that is, the velocity gradient would be directed away from the center of curvature. It is necessary, then, to demonstrate that in the crossover reach of a natural river meander, the circulation vector is not zero.

Conservation of circulation in fluid flow--The actual situation in a river meander is more complicated, however. Bed friction causes the surface streamlines to move across the stream away from the center of curvature while the streamlines near the bed turn toward the inner or convex bank.

The circulation is then not merely shear in the plan view of the velocity field, but consists of shear in each of three planes. Moreover, the cross-sectional area of flowing water changes from crossover to the center line of the bend and thus leads to divergence and convergence which affect the flow pattern.

The basic postulate made here is that in the flow in a meandering river, the circulation is conserved, or

$$dC/dt = 0$$

where C is circulation having the units of moment of momentum or ft^2/sec. Let vorticity ω be defined as

$$\omega = \delta C/\delta A$$

or circulation per unit area. Vorticity ω can be resolved into three components, ξ, η, and ζ about the axes x, y, and z, where

$$\xi = \partial v_y/\partial z - \partial v_z/\partial y$$

$$\eta = \partial v_x/\partial z - \partial v_z/\partial x$$

$$\zeta = \partial v_y/\partial x - \partial v_x/\partial y$$

where v_x, v_y, and v_z are the components of velocity in the x, y, and z directions.

It can be shown that if circulation is conserved or

$$dC/dt = 0$$

then the rate of change of vorticity equals the product of vorticity times divergence, with a minus sign,

$$d\omega/dt = -\omega[\partial(\rho v_x)/\partial x + \partial(\rho v_y)/\partial y + \partial(\rho v_z)/\partial z]$$

or

$$d\omega/dt = -\omega(\text{div } V)$$

It is further necessary, therefore, to prove that this equality is actually maintained at various points along the meander wave in a natural river.

Application to a natural meander--To test the hypothesis that the equation is satisfied, the author measured, with the help of John P. Miller, the horizontal velocity components in a natural meander of Baldwin Creek near Lander, Wyoming. The total horizontal velocity vector at a given point was measured by current meter, and its direction noted by a specially constructed direction vane attached to the wading rod. Baldwin Creek at the time of measurement carried 36 cfs, had a width of 20 ft, an average depth of one to two feet, and the meander wave length was 160 ft, amplitude 130 ft.

For the numerical integration the wave length was divided into 16 reaches along the stream. The width of the stream was divided into five parts, and horizontal slabs 0.4 ft in vertical thickness were used. Thus the flow was described by velocity through each of the six sides of unit volumes about 20 ft long, 4 ft wide, and 0.4 ft deep. Numerical integration was made with the assistance of M. Gordon Wolman.

The scalar values of the two sides of the equation

$$d\omega/dt = -\omega(\mathrm{div}\ V)$$

were computed and are plotted in Figure 1a on the ordinate scale. The values of $d\omega/dt$ are represented as open circles and of $-\omega(\mathrm{div}\ V)$ as crosses. The abscissa represents the positions along the meander wave. If the postulate is true that circulation is conserved in a natural meander, the crosses and circles should coincide on the ordinate scale. Though the correspondence is not exact, the values are of the same order and change sign along the meander wave in a remarkably consistent manner. It appears, then, that within the limit of error of the field data and integration method, circulation is conserved in the natural meander studied.

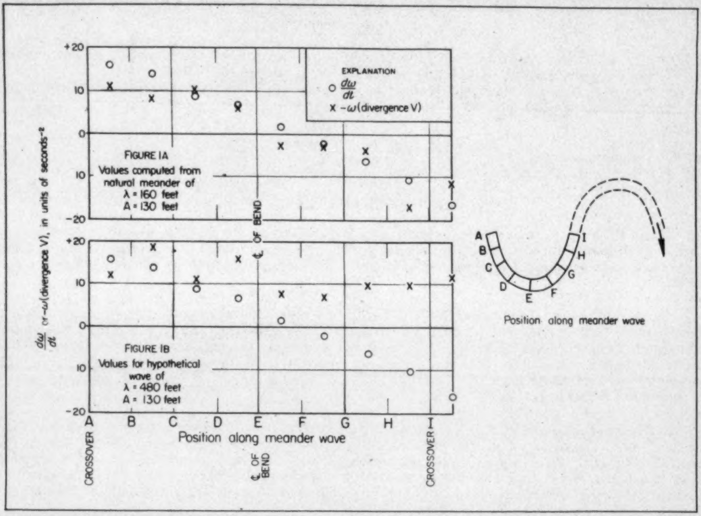

Fig. 1--Variation of the quantities $d\omega/dt$ (open circles) and $-\omega(\mathrm{div}\ V)$ (crosses) along the meander wave; (a) data for a natural meander in which the two quantities are roughly equal; (b) data for a hypothetical wave having a larger wave length shows inequality of values

Using the same velocity distribution, the quantities were recomputed along a hypothetical meander wave having the same amplitude but a wave length of 480 ft, three times the actual wave length in the real river. The plot of $d\omega/dt$ and of $-\omega(\mathrm{div}\ V)$ versus position along the wave are shown in Figure 1b. It can be seen that the equality of values is not maintained; that is, circulation is not conserved. This suggests, then, that a natural meandering river forms meander waves of such a length that the circulation is conserved, and, therefore, the conservation of circulation is basic to meander formation.

The river data studied showed that velocity is not uniformly distributed in the cross section of the crossover, but rather the largest velocity is nearer the bank which was the outside or concave bank in the curve immediately upstream. If circulation is conserved the straight reach should be succeeded by a curve such that the center of curvature lies on the same side of the stream as the greatest velocity in the straight reach, just as in the Wattendorf flume. The present theory, then, provides a mechanism for the development of a curve below the point of inflection or crossover, and the curvature will be opposite in sign to that of the bend immediately upstream.

It is postulated that formation of meanders depends on the preservation of the circulation through

a reach of channel. This circulation would be dissipated by small scale eddies if the velocity-depth ratio were large, whereas it would be conserved rather than dissipated in a channel having a small value of the velocity-depth ratio. It has been demonstrated [LEOPOLD and MADDOCK, 1953] that in upstream reaches of rivers the velocity-depth ratio is large and decreases downstream. It is reasoned, therefore, that meanders occur primarily in the downstream reaches of rivers for that reason. This is in agreement with the observation that meanders occur in headwater tributaries only where depth is large relative to velocity.

A more complete treatment of this problem will be published after the investigation has been pursued further.

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OCEANOGRAPHY IN INDIA

It has been the pleasure of the writer to visit India during the academic year, 1952-53. Although affiliated with the Andhra University, Waltair, he was enabled to travel to all major cities and discuss the oceanographic progress and plans with many scientists in this newly independent country.

During the British administration the major oceanographic work was carried on by R.B.S. Sewell while Surgeon-naturalist and later Director of the Zoological Survey of India. Now Indian Government agencies are beginning to sponsor oceanography through the Fisheries Department, The Navy, and universities. This work is co-ordinated by a National Committee on Oceanography set up by the Central Geophysical Board of India. Plans have also been made to establish an Indian Institute of Oceanography.

Some oceanographic work is currently being undertaken by the Department of Fisheries, both by the Central Government and the sea-coast State Governments, especially Bombay, Madras, and Bengal. One of the most active Fisheries Stations under the Ministry of Food and Agriculture is at Mandapam, South India; another substation is located at Kozhikode. At present their main efforts are devoted to surface observations of seasonal variations in sea temperatures, chemical composition of sea water, and plankton.

The Indian meteorological department has been active for a great many years in the collection of data, gathered from ships and coastal stations, on sea state, swell, density, waves, and currents. Some studies of turbulence and evaporation have been made on shipboard. They are also engaged in work on microseisms and have a tripartite microseismograph in operation in Madras, and another is to be installed in Bombay.

The Indian Navy has recently established a research laboratory at Cochin, on the west coast, where research on underwater sound and oceanography is being undertaken. They are now in the process of setting up a wave recorder, and are also studying the vertical thermal structure of the sea. Future plans call for seismic studies of the sea floor. This work will be under the direction of N. Nanda, recently of the Carnegie Institution of Washington.

The survey ship INS Investigator conducts hydrographic investigation along the extensive 2900-mile coast of India. The Survey of India also maintains continuous tidal recording stations in all major ports.

The teaching of Oceanography is carried on at Andhra University, Waltair: physical oceanography in the Geophysics Department; marine geology and marine zoology in the Geology and Zoology Departments, respectively. The University is conveniently located on the central part of the east coast adjacent to an excellent harbor, Visakhapatnam. Formerly only a catamaran was available for sea work. More recently the harbor authorities, and especially the Navy, have cooperated with the University by periodically furnishing ships for oceanographic cruises. Eighteen cruises have been made out of Visakhapatnam along the east coast between Calcutta and Madras, and one extending around the southern tip of India to Cochin. On these cruises students are trained in the operation of oceanographic gear and in the procedure of making oceanographic studies. The waters of the eastern coast are especially interesting, primarily because the currents are completely reversed when one monsoon is replaced by the other, but also because there is great dilution from the enormous rivers, the many long deltic channels of the Ganges river are ideally suited to estuarine oceanography, the submarine canyon Swatch of No Ground probably sets forth turbidity currents, and both upwelling and sinking appear to be present at different seasons.

Equipment is still meager but is gradually being built and purchased. Mine-sweeper sweep winches have proven satisfactory, though slow, for lowering equipment.

Some students have also gone abroad for higher degrees and oceanographic training. Varadachari is now attending Florida State University, Sitlani is at the University of Washington, and P. S. Pant plans to carry on work at New York University. Two others have taken some oceanography courses at the University of Washington and are now engaged in fisheries work.

The enthusiasm for oceanographic work at Andhra University and the splendid cooperation of other Government agencies promise substantial contributions to the study of the Indian ocean. In order to assist in promoting oceanography in this neglected area, the writer recommends that the following organizations be put on mailing lists for publications in the appropriate fields of oceanography: Andhra University, Waltair, South India; Naval Physical Laboratory, Cochin, South India; Fisheries Research Station, Mandapam, South India; and Secretary, Committee on Oceanography, Central Board of Geophysics, 27, Chowringhee Road, Calcutta 13.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

LYTTLETON, R. A., The Stability of Rotating Liquid Masses, Cambridge University Press, 150 pp., 1953, $6.50.

The recent revision of the astronomical time-scale of the universe should intensify an already lively interest in the problems of the evolution of a stellar or solar system. Past investigators, notably Darwin and Jeans, regarded fission as a dynamically feasible mechanism for the production of stable binary systems, and this belief has retained considerable scientific currency. Lyttleton, after an extensive review of the mathematical investigations entering into this question, concludes that binary stars cannot have been produced by fission. For the solar system, however, he gives a plausible descriptive account of a fission mechanism for the formation of the smaller planets from large protoplanets which were themselves, he assumes, detached in some way from a companion star to the Sun.

Apart from the interest in this book which responsible cosmogonical speculation must always arouse, there should be additional interest in a book which, though in large part mathematical, is still an understandable introduction and guide to a field hitherto obscured from many of us by its complexity.

Lyttleton has gathered and organized the many source materials, ranging from the work of Maclaurin and Clairaut in the 1700's to that of Cartan in the 1920's, and has made the present status of the problem of the stability of rotating liquid masses reasonably accessible to the non-specialist.

ALFRED D. SOLLINS

RUSSELL, R. C. H., and D. H. MACMILLAN, Waves and Tides, Philosophical Library, New York, 348 pp., 1953, $6.00.

The title of this book might convey the impression that it treats of all periodic disturbances of the sea surface, from those with periods of seconds to those of periods in days. Such, however, is not the case. Russell's portion, the first 163 pages, deals exclusively with wind-generated surface waves; Macmillan's section is almost entirely devoted to discussion of astronomical tides, with only brief mention of storm surges, seismic phenomena, and seiches. Tsunamis, power spectra, microseisms, surf beats, or internal waves, all familiar to readers of the *Transactions*, are not mentioned.

The book fills part of the void that now exists between the non-mathematical popular works on the sea like Rachel Carson's and the elegant expositions of hydrodynamic theory. It is designed to introduce the layman to the field, and, without burying him in exhaustive citations, to indicate where further material is available. As far as tides are concerned, there is little new to be said; but most of the research described on wind waves has been accomplished within the last dozen years, and has not previously been summarized between a single pair of covers.

Recognizing that there is still much that is controversial about the behavior of waves, Russell bases his chapters on the opinion of the writer and "those from whom he derives his opinion." After discussing the general characteristics of ocean waves and the properties of ideal waves, he covers generation by wind, reflection, refraction, diffraction, conversion into breakers, movement of material by the sea, and effect on structures, and he concludes with a brief chapter on wave measuring.

Macmillan is more concerned with describing all possible astronomical influences on the tides than with the basic cause of tides, with the result that the reader will have difficulty in understanding why, although the Moon seems to travel around the Earth only once daily, there are usually two tides in the same period. The explanation that the centrifugal force between astronomical bodies holds them apart just as gravitation holds them together, and that the forces, though they are equal and opposite on the average, vary from position to position on the bodies, is not explicitly set forth. Coriolis force is described only as "gyroscopic effect."

The 16 plates and numerous text figures are well chosen to clarify the text. There is an excellent index, although the indexer has failed to notice that Russell's "tidal currents" are the same as Macmillan's "tidal streams." On page 18, a value of 64 lb rather than 62.5 should have been given as the weight of a cubic foot of sea water.

JOHN LYMAN

SEGRE, E. (Editor), H. STAUB, H. BETHE, J. ASHKIN, N. F. RAMSEY, and K. T. BAINBRIDGE, Experimental Nuclear Physics, Vol. I, John Wiley and Sons, 789 pp., 1953, $15.00.

Since the close of World War II a great deal of previously classified information and techniques have found their way into the literature. As Segre points out, many of the physicists engaged in this war research as well as many younger physicists have turned to fields of academic nuclear research, and there is a need of a book to indicate the results of the past work and its theoretical significance. Although the purely theoretical aspects of nuclear physics have been adequately covered in recent publications, there is a need to bring experimental nuclear physics up to date. These authors have made an excellent presentation of the experimental data and its interpretation.

In spite of the fact that nuclear physics has become so specialized, it is an exceedingly difficult task, because of its complexity, to classify it into individual subjects. The authors, however, have accomplished a logical analysis. The text is divided into five parts, namely, (1) detection methods, (2) passage of radiations through matter, (3) nuclear moments and statistics, (4) nuclear two-body problems and elements of nuclear structure, and (5) charged-particle dynamics and optics, relative isotopic abundances of the elements, and atomic masses. Each part is divided into three or four sections, each section being further classified into divisions and subdivisions. It is thus very easy to pin-point a particular piece of information without thumbing through a large part of the book. The development of the experimental techniques is supplemented by a large amount of data in the text, numerous graphs, and 44 tables. Well over 1900 references are made to contributions of other investigators.

This book not only provides background material for many specialized fields of nuclear research, but also, owing to the large amount of quantitative information, serves as an excellent reference book. For this reason and because it has such complete coverage of experimental data, this reviewer highly recommends this book for those interested in the field of nuclear physics.

FRANK E. SENFTLE

STEWART-REMINGTON, JOHN, and WILFRID FRANCIS, The Composition and Assaying of Minerals, Philosophical Library, New York, viii + 128 pp., 1953, $5.50.

This is a peculiar book. It purports to list the principal ore minerals of the useful metals, with localities of ore deposits; to give methods for the qualitative identification of the components of the minerals of the various metals; and to give methods for the quantitative determination of the constituent elements of the ores listed, and of the common rock-forming minerals. In none of these points is the purpose fulfilled.

The mineral nomenclature is over 30 years out of date; the analytical methods are, in too many cases, those of 30 to 40 years ago. It is difficult for the reviewer to believe that, as stated in the preface, the original manuscript was prepared as recently as 1940. Serious errors, apparently due to inadequate proof-reading, also appear. The reviewer finds on the average of one correction to a page to be needed, let alone matter that has been left out. For the American reader there is the additional difficulty that the chemical terms are purely British, and several may be unfamiliar to him.

A skilled mineral or ore analyst may find a few useful professional hints, but the book should not, in the reviewer's opinion, be put into the hands of a student.

JOHN PUTNAM MARBLE

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NOTES AND PERSONALIA

NOTES

National Science Foundation awards--The following awards for work bearing on geophysics have been made by the National Science Foundation:

Pennsylvania State College (A. H. Waynick), Detecting solar and upper atmosphere phenomena by long-wave radio methods, one year, $12,000.

Princeton University (W. T. Thom, Jr.), Crustal deformation in portions of the Great Plains and Cordilleran regions, one year, $8700.

Columbia University (W. H. Bucher), Geologic investigation of the tectonic settling of landmasses adjacent to the Puerto Rican Trench, one year, $14,000.

University of Chicago (H. C. Urey), Isotopic abundances relating to geochemical research, one year, $21,400.

Brown University (R. B. Montgomery), Analysis of serial oceanographic observations, two years, $12,200.

Wayne University (W. H. Parsons), Igneous geology in the Beartooth Mountain area, Wyoming, Montana, six months, $4000.

University of Nebraska (R. L. Threet), Structures of the Colorado Plateau Margin in southwestern Utah, two years, $4400.

University of Miami (R. N. Ginsburg), Geological role of some blue-green algae, six months, $3300.

University of Illinois (G. H. White), Properties of glacial tills, 15 months, $11,800.

State University of Iowa (R. B. Wylie), New methods in leaf research, 15 months, $5400.

Atomic Energy research contracts--The following contracts bearing on geophysics have recently been awarded by the Atomic Energy Commission:

Columbia University (J. L. Kulp), Uranium-lead method of age determination, $30,348.

Massachusetts Institute of Technology (P. M. Hurley), Investigations of isotopic abundances of strontium, calcium, and argon in certain minerals, $29,630.

University of Arkansas (R. R. Edwards), Investigation of the radioactivity of thermal waters and its relationship to the geology and geochemistry of uranium, $22,000.

Graduate assistantships in meteorology at Florida State University--The Department of Meteorology of the University announces the availability of graduate assistantships on research both for holders of baccalaureate degrees (stipend $1620) and for holders of masters degrees (stipend $1920). For application forms and for additional information, address the Department of Meteorology of the University of Tallahassee.

Meteorology at the University of Michigan--Teaching and research on the engineering applications of meteorology are being developed by the Department of Civil Engineering and the Engineering Research Institute. Cooperative research on the atmospheric diffusion and penetration into buildings of allergenic pollens and industrial contaminants is being undertaken in association with the School of Public Health; the project is sponsored by the Geophysics Research Center, Directorage of the Air Force Cambridge Research Center.

Third International Conference on Soil Mechanics and Foundation Engineering--This conference was held in Zurich, August 14-27, 1953, with about 800 in attendance from 30 countries, and included a four-day field trip. Over 150 papers were presented. About 50 attended from the United States, including A. E. Cummings of New York.

Commission on Geochemical Localization of the Elements--This Commission of the International Union of Chemistry held its first symposium in Zurich, August 11-13, 1953. A total of 65 from 18 countries were in attendance, and 35 papers were presented. Among AGU membership in attendance were Tom. F. W. Barth, Earl Ingerson, and H. C. Urey. The main theme of the meeting was the problems of organizing geophysical data, making it available, and keeping scientists informed concerning active research programs. The symposium was followed by a two-day field trip to Eastern Gotthard.

Advisory Panel on Minerals Research--The National Science Foundation has recently established a Panel on Minerals Research which includes the following: Alan M. Bateman, Gordon L. Davis, Maurice Ewing, Paul D. Foote, L. C. Graton, Thomas Nolan, William W. Rubey, Louis B. Slichter, John W. Vanderwilt, and William E. Wrather.

The new oceanographic vessel of Texas A and M--The new oceanographic vessel of Texas A and M College has been renamed the A. A. Jakkula in memory of the late Executive Director of the Texas A and M Research Foundation.

New publication of the Tulsa Geological Society--Volume 21 of the Society is the largest of the volumes thus far published containing 25 geological papers in its 267 pages. Interested persons should write to E. T. Peterson, c/o Atlantic Refining Co., 830 Kennedy Bldg., Tulsa, Oklahoma.

Southwestern Conference of Institute of Radio Engineers--The Sixth Southwestern Conference will be held in Tulsa, Oklahoma, February 4-6, 1954. Arrangements are in the charge of Daniel Silverman and Charles F. Hadley, P. O. Box 591, Tulsa, Oklahoma.

PERSONALIA

Rogers Adams, Head of the Department of Chemistry at the University of Illinois, has been given the 1953 Midwest Award of the St. Louis Section of the American Chemical Society for "meritorious contributions to the advancement of pure or applied chemistry or chemical research."

Louis H. Ahrens, Assistant Professor of Geochemistry in the Department of Geology and Geophysics, Massachusetts Institute of Technology, has resigned to accept a Readership in Mineralogy at Oxford University commencing in January, 1954. He is widely known for his spectrochemical research on geological age and will continue similar work in England.

Maurice L. Albertson, Professor of Civil Engineering at Colorado A and M College, is on leave, studying at Neyrpic Laboratories and the University of Grenoble, France, on a Fulbright Scholarship.

Robert F. Black of the U. S. Geological Survey has accepted an appointment with the Foreign Operations Administration for geological work in Mexico.

Wayne V. Burt, formerly of the Chesapeake Bay Laboratory of Johns Hopkins University at Annapolis, Maryland, is now on duty in the Department of Oceanography of the University of Washington as a Research Oceanographer.

Peter Dehlinger, until recently with the Battelle Memorial Institute in Columbus, Ohio, has accepted a position as Research Associate with the Continental Oil Co. with headquarters in Ponca City, Oklahoma.

David E. Donley of the Bureau of Reclamation is in Lebanon for the Foreign Operations Administration as hydrologist on the development of the Litani River.

John G. Duba, formerly Assistant Professor of Civil Engineering at Illinois Institute of Technology, has accepted a position as engineer in the Chicago Department of Public Works.

Herbert E. Hawkes, recently Chief of the Geochemical Prospecting Section of the U. S. Geological Survey, Denver Federal Center, has joined the staff of the Department of Geology and Geophysics at the Massachusetts Institute of Technology as Lecturer in Geochemistry. He will conduct one course in Geochemical Prospecting and will carry on geochemical research at the Institute.

P. R. Heenan has entered upon geological duties with the O'Brien Gold Mines, Ltd. at Kewagama, Que., Canada.

Marvin D. Hoover who has been on research work for the U. S. Forest Service at Union, South Carolina, has been named Chief of the Division of Forest Influences at the Rocky Mountain Forest and Range Experiment Station at Ft. Collins, Colorado.

E. W. Lane, who has been serving as Consultant for the Bureau of Reclamation, has accepted an appointment as Professor of Civil Engineering at Colorado A and M College.

Robert F. Legget, Director of the Division of Building Research of the National Research Council of Canada, has been elected Honorary Fellow of the Royal Architectural Institute of Canada.

Walter C. Lowdermilk, world-renowned conservationist and past President of AGU, has returned to the United States following a three-year sojourn, much of which was devoted to problems of Israel and the Jordan Valley under the auspices of the Food and Agricultural Organization of the United Nations.

Samuel B. Morris, General Manager of the Department of Water and Power of the City of Los Angeles, has been named a Director of the American Society of Civil Engineers. He also recently received an honorary doctorate from the University of California.

Frank Press, Associate Professor of Geology at Columbia University, is now on a three-month UNESCO appointment on the technical assistance program to Israel, supervising the installation of two seismograph stations and training the staff for their operation.

John E. Sanders has been appointed a Post Doctoral Fellow of the National Research Council and will devote his time until late summer of 1954 on study in Europe.

J. R. Schander has resigned as geologist and geophysicist for the Cockburn Oil Corp. and has entered upon similar work with Albert Plummer, oil operator of Houston, Texas.

Edmund Schulman of the University of Arizona is currently serving as Visiting Professor of Dendrochronology at California Institute of Technology.

Victor Vacquier, President of the Section of Terrestrial Magnetism and Electricity, has left his work with the Sperry Gyroscope Co. and Columbia University, and has taken up duties at New Mexico Institute of Mines and Technology.

William E. Wrather, Director of the U. S. Geological Survey, has been awarded the John Fritz Medal for 1954. This is an award of the four Founder Societies of engineering.

Scotland G. Highland, Secretary and General Manager of the Clarksburg, W. Va., Water Board, died October 25, 1953 at the age of 74. He was born near West Milford, W. Va. He graduated from Iron City College in Pittsburgh, later taking work at the University of West Virginia. He was a pioneer in watershed and runoff studies in West Virginia, establishing rain gages, soil thermometers, a stream gage, and other equipment in the second decade of this century on the watershed from which Clarksburg secures its water supply. He was identified with this work most of his adult life. He had been a member of AGU since 1945.

Harry A. Marmer, who retired as Assistant Chief of the Division of Tides and Currents, U. S. Coast and Geodetic Survey, last August, died November 5, 1953 at the age of 68. He was born in the Ukraine in Russia, coming to the United States at the age of four. He received his baccalaureate degree from Rutgers University in 1907, and entered upon duty with the Survey that same year. He was a recognized world authority on many matters relating to the oceans, notably tides, and was the author of two books, one entitled The Tide, and the other The Sea. He was awarded the Alexander Agassiz Medal of the National Academy of Sciences for his original scientific work in oceanography, and in 1949 received the Gold Medal of the Department of Commerce for exceptional service. He had been a member of AGU since 1924, served as Secretary of the Section of Oceanography from 1929-1932, and as President of the Section from 1932-1935.

Marcel E. H. Schlumberger, Director of Schlumberger Well Surveying Corp. of Houston, Texas, and President of Société de Prospection Électrique and of Compagnie Générale de Géophysique of Paris, died suddenly at his home in Normandy, France, August 20, 1953 at the age of 69. He was born at Guebwiller, Alsace. He graduated as a Civil Engineer from Ecole Centrale des Arts et Manufactures in 1907. His remarkable inventive genius, resourcefulness and perserverance led him to various positions as research engineer or consultant. He received the Legion of Honor for his work in World War I. Subsequently, in association with his brother, Conrad, he developed the new science of electrical prospecting, for which he and his brother received the Anthony F. Lucas Gold Medal of the American Institute of Mining and Metallurgical Engineers. He had been a member of AGU since 1947.

SPECIAL ANNOUNCEMENTS

Pacific Southwest Meeting at the University of Southern California, January 29-30, 1954--Plans are developing rapidly for this annual meeting which will be held at the University of Southern California in Los Angeles, January 29-30, 1954. The Sections of Meteorology and Hydrology are joining in this, but there is yet time for other Sections to join. John Mann of USC is in charge of local arrangements, and the program for the Section of Hydrology. H. H. Engelbrecht is in charge of arrangements for the program in Meteorology. Martin R. Huberty (Professor of Irrigation, University of California, Los Angeles, Calif.) is Chairman of the Pacific Southwest Regional Committee, and R. Corday Counts (U. S. Weather Bureau, San Bruno, Calif.) is Secretary, Other members of the Committee are H. H. Engelbrecht, H. McV. Stafford, Vito A. Vanoni, and C. F. Woffinden.

Thirty-Fifth Annual Meeting, Washington, D. C., May 3-5, 1954--Your attention is called to the extended notice concerning this meeting on page 823 of the October issue of the Transactions. Note that titles and abstracts of papers for the program should be in as soon as possible, and not later than March 10, 1954. Abstracts must be informative and concise. Remember that Secretaries reserve the right to close programs filled in advance of March 10. Complete manuscripts should be in the AGU office by April 15, with advice as to whether the paper is also submitted for the Transactions. Also, send in word concerning projection equipment requirements. Standard (3 1/4 × 4 inches) slide projector will normally be available. Communications should be sent to the appropriate Secretary or Program Chairman [see Oct. issue, page 823] or to the AGU office.

In preparing your paper for presentation, bear in mind that requirements are quite different than for publication. We might borrow the succinct instructions of the Association of Seismology, IUGG, at the Brussels Meeting in the summer of 1951: "Speak slowly, clearly, and briefly; avoid mathematics."

Block bookings have been made at three hotels as follows:

Roger Smith Hotel, Pennsylvania Avenue at 18th Street, Northwest
Raleigh Hotel, Pennsylvania Avenue at 12th Street, Northwest
Washington Hotel, Pennsylvania Avenue at 15th Street, Northwest

Most of the block-booked rooms are at the Roger Smith Hotel (the one nearest the meeting place) and the Washington Hotel.

Make your hotel or room reservation early directly with the hotel of your choice. If you request block-booked space, be sure to cite the AGU meeting.

Tenth General Assembly, International Union of Geodesy and Geophysics, Rome, Italy, September 15-29, 1954--Program plans are now developing rapidly for all the Associations and for the Union as a whole. Those who are planning to attend should advise the office of AGU as soon as possible, in order to be placed on the mailing list for special information as it becomes available, and in order that we may advise the Italian National Committee of accommodation needs. You should also make travel arrangements soon, especially if travel is to be by boat. There is a possibility of chartering a special plane, and if sufficient numbers are going and returning at one time, it is possible that a per-capita rate for transportation alone as low as $200 for the trip one way may be obtained. Let the office know if you are interested in this possibility.

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